An Overview of NASA's HSR Program:
Environmental Issues and Economic Concerns

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Abstract. This paper gives a brief overview of the NASA's High-Speed Research (HSR) Program. Included will be a short discussion of the market projections for a High-Speed Civil Transport (HSCT) and approaches which have been taken to address both the environmental and weight concerns of such a vehicle.

1 INTRODUCTION

When the United States' SST Program was canceled in 1971, the environmental factors of sonic boom, noise, and to a lesser extent, ozone depletion, played a role in the decision. Since that time, FAA noise rules have become increasingly stringent, the appearance of ozone holes in the atmosphere has caused alarm for public safety, and many nations around the world have enacted legislation prohibiting supersonic flight by commercial transports over their territory because of the sonic boom.

The current NASA High-Speed Research (HSR) Program, a research program which focuses on technologies needed for the development of an environmentally friendly, economically viable HSCT, was initiated in 1990 at the culmination of feasibility studies conducted by McDonnell Douglas and Boeing. The recommendation from these two major airframers was that although there appeared to be no show-stoppers to the development of an HSCT, the HSR Program should be implemented in phases. It was recommended that Phase I, which began in 1990, would take a more in-depth look at the critical environmental concerns associated with a supersonic transport. Critical technology advances needed for an economically successful supersonic transport would be addressed in Phase II--and then only after Phase I studies indicated no show stoppers in the environmental area. Phase I, which ended in 1995, placed emphasis on the development of a low-noise, low-NO_x-combustor propulsion system, enhanced low-speed lift characteristics (for low-noise), sonic-boom minimization, and understanding the impact of atmospheric radiation. The results of Phase I indicated that none of the environmental issues were show-stoppers.

Phase II of the HSR Program, which began in 1995 and will continue through 2002, has focused on technologies needed to make the HSCT economically viable--affordable by a large percentage of the passengers on long, international, overwater routes. During this phase, great emphasis has been placed on weight reduction through: higher lift-to-drag ratios; external vision to eliminate the need for droop-nose; and lighter, damage tolerant, and more durable composite materials and structures. Sophisticated use of super computers with computational fluid dynamics (CFD), design optimization, and finite-element modeling (FEM) have contributed and continue to contribute significantly to advances in these technologies.

Though the phases of the program have been divided into economic considerations and environmental considerations, the two are not mutually exclusive since in many instances, steps taken to mitigate environmental risks impact the economic viability of the aircraft. This paper will give a brief review of the studies which indicated there would be a market for an HSCT, the environmental studies conducted in Phase I to ensure its friendliness to our environment, and the technology development studies which are continuing in Phase II. Flight tests, conducted in 1996-98 using the Russian Tu-144 will also be briefly discussed.

2 BACKGROUND

In addition to market projections, the feasibility studies performed by Boeing and McDonnell Douglas included consideration of economics, range, Mach number, fuels, payload and technology needs. An assessment of the world market and flight time between city pairs such as New York or Los Angeles, Paris, and Japan indicated that these heavily traveled routes are projected to grow significantly in the first decade of the 21st Century and would require a non-stop range of 5000 to 6000 n.mi. Initially, Mach numbers from 2 to 25 were considered, but the contractors quickly realized that little productivity was gained beyond Mach 5 because of range, block time, flight restrictions, and other factors. For the maximum range vehicle, the effect of cruise

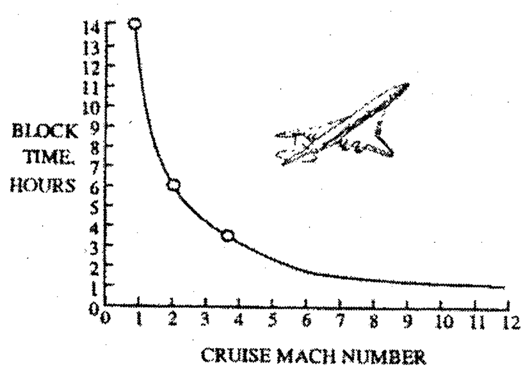

Figure 1 - Effect of speed on block time.

Mach number on block time is shown in Fig 1. Because the choice of Mach number also impacts aerodynamic shape, the types of materials, and the type of fuel, the ability to use the existing infrastructure was also a decision factor.

Another factor considered by the contractors was that of passenger fares. While supersonic speeds are attractive, the fare premium for the Concorde is such that most prospective passengers are lost to the subsonic market. Such would also be the case for a second-generation supersonic transport if it also required large fare premiums. Studies indicate that fare premiums should range between 10 and 20 percent of the going subsonic rate in order for the HSCT to be competitive.

Based on the above considerations, the contractors recommended[1,2] that the United States initiate a joint Industry/NASA technology program which could lead to the development of a HSCT able to cruise at Mach 2.4, have a range of 5,000 to 6,500 n.mi., accommodate 250 to 300 passengers, meet FAR 36 Stage 3 noise rules, and have a takeoff gross weight between 700,000 and 800,000 lb. Flight times when traveling at Mach number 2.4 are compared to subsonic flight times on typical Pacific routes in Fig. 2. The trip from Tokyo to Los Angeles is reduced from 10.3 hours to approximately 4.3 hours, and a non-stop 14 hour subsonic trip from Los Angeles to Tokyo reduces to a 7.3 hour trip with one stop in Honolulu.

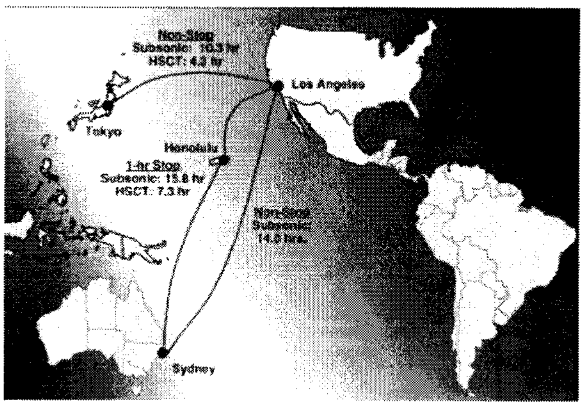

Figure 2 - Trip time comparisons.

The contractors divided their concerns into environmental-compatibility requirements and technology needs. The technology areas and suggested approach recommended in the feasibility study reports served as the basis for the current NASA HSR Program. In order to evaluate the impact of advances in any of the technology areas, systems studies have been an ongoing component of the program.

3 ENVIRONMENTAL CONCERNS

Based on earlier recommendations, the objectives of the Environmental Studies component of the HSR program have been to: (1) assess the levels of radiation exposure during supersonic cruise; (2) determine emission levels necessary for no impact on the ozone layer and develop technologies necessary to produce those levels; (3) develop noise reduction technologies which would enable compliance with current noise rules; and (4) pursue sonic boom reduction technologies and assess the impact of resulting sonic boom levels.

3.1 Atmospheric Radiation.[3] Atmospheric ionizing radiation incident on the Earth's atmosphere is attributable to three sources: galactic cosmic rays which originate from outside the solar system, steady-state solar-generated cosmic rays, and transient solar particle events. These high-energy subatomic particles collide with atoms of oxygen, nitrogen and other atmospheric constituents and spawn additional subatomic particles. Although the intensity of the galactic and solar radiation penetrating through the atmosphere to the ground is low, levels at commercial flight altitudes are more than two orders of magnitude greater. Because the atmosphere acts as a radiation shield, the higher altitude of the HSCT would result in even higher incident radiation on the aircraft hull, Fig. 3.

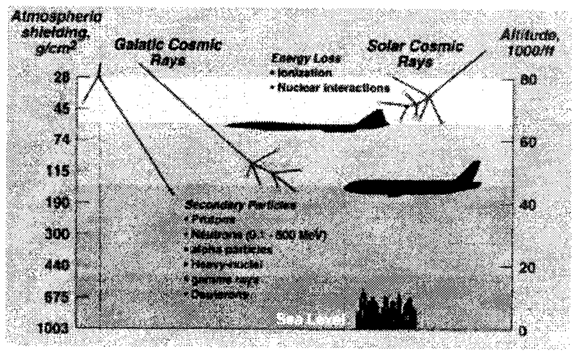

Figure 3 - Radiation exposure.

The focused goal of this program element is to develop an improved atmospheric ionizing radiation (AIR) model to reduce uncertainties in the atmospheric radiation components by 20 percent in order to improve the prediction of health risks to passengers and crew. Special emphasis has been given to the high-energy neutrons in the altitude range of 50,000 to 70,000 ft. The results will be expressed in an environmental model able to represent predicted radiation levels--including their spectral and angular distributions. This information will allow predictions to include aircraft

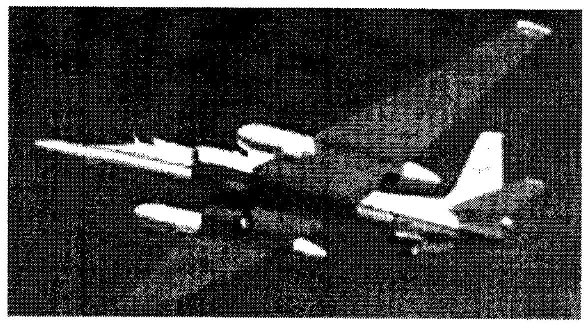

Figure 4 - Photograph of the ER-2 during takeoff.

shielding properties. The impact of solar cycles and events on radiation levels will be included in near-real time through satellite system data.

To provide a data base for validating radiation models, a flight test was conducted from the NASA Ames' Moffett Field, CA, using the ER-2 aircraft (shown in Fig. 4) a derivative of the high-altitude reconnaissance U-2. Measurements of radiation levels were taken as a function of latitude and longitude at altitudes up to 70,000 ft. Six missions were flown along the flight tracks parallel and perpendicular to lines of constant geomagnetic strength as shown in Fig 5. Early studies have shown that the heavily traveled northern Atlantic and Pacific corridors are subject to the highest radiation levels because the Earth's magnetic field deflects a significant portion of the incident radiation near the equator.

Because the HSCT flies at greater than twice the speed of its subsonic counterpart, passengers on either airplane will nominally receive about the same overall dosage for a given trip. Of greater concern would be the exposure of the HSCT flight crews, since they would nominally fly the same number of flight hours at high altitude. A possible solution by the airline could be to monitor radiation dosage of its crews and use crew rotation to maintain safe levels of exposure.

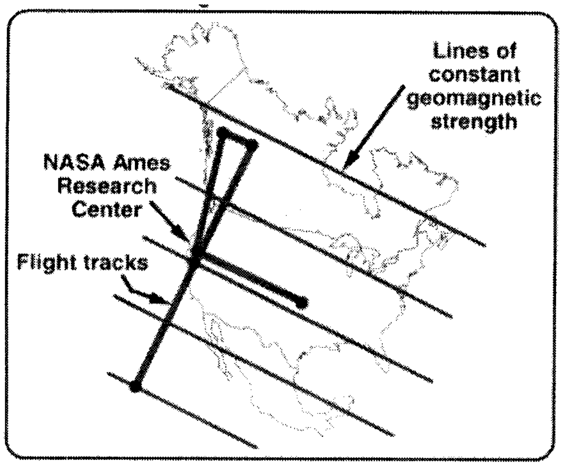

Figure 5 - Flight tracks flown using ER-2 to collect radiation data.

3.2 Ozone Depletion. A major environmental concern of supersonic flight is the depletion of stratospheric ozone.[4] Ultraviolet rays break down stratospheric ozone into molecular and atomic oxygen. These molecules later reunite to form new ozone which helps to protect the Earth from ultraviolet rays. The nitrogen oxide (NO_x) emissions found in airplane jet exhausts react with ozone and convert it to molecular oxygen. Because the HSCT would fly at the altitude at which ozone is maximum, near 60,000 ft., the NO_x emissions would be immediately damaging to the fragile ozone layer. The inability to control these emissions and protect the ozone layer is an environmental issue often called a "show-stopper."

The approach to this issue has been three-fold: (1) assess the impact of exhaust emissions on ozone chemistry; (2) determine an acceptable NO_x emissions index, if it exists; and (3) develop a combustor and engine which meet the acceptable emissions index.

To address the first two issues, the Atmospheric Effects of Stratospheric Aircraft (AESA) element was formed in Phase I of the HSR Program.[5] Under this program element, an international team of scientists has developed and applied global atmospheric models to predict the impact of nitrogen oxides, water vapor, and other exhaust emissions on ozone chemistry and climate change. Model results indicate that the amount of stratospheric ozone is determined by photochemical production and loss processes and by the transport of air throughout the atmosphere.

Emissions indices (EI) for the HSCT engine are expressed as the ratio of grams of exhaust constituent to kilograms of fuel consumed. Exhaust constituents of importance to the models include carbon monoxide, carbon dioxide, water, nitrogen oxide, and sulfur dioxide. To predict impact, operational scenarios of the HSCT within a simulated route structure are developed, fuel burn and emissions are calculated for each city pair flight, and data from these scenarios are introduced into atmospheric models which then predict the steady state effect on the ozone layer. The 2- and 3-dimensional photochemical transport models used are calibrated using laboratory chemical kinetics tests and atmospheric measurements made with the ER-2 and weather balloons.

On at least one occasion, the ER-2 measured the exhaust of the Concorde--providing valuable data for near-field atmospheric interactions. Soot and sulfur particles were present in the Concorde exhaust at a far higher level than anticipated.

Emissions Index. During the early phase of the HSR program before any detailed propulsion components were designed or tested, the planning team projected that admissible emission levels should be within an EI range of 3 to 8 to meet the HSR program goal that the airplane have no significant impact on the ozone layer.

Fig. 6 presents a set of those early model results in which steady-state ozone loss is plotted against annual production of NO_x from projected HSCT operations. The bands represent the variations produced by the five independent atmospheric models that were a part of the AESA program. Because the number of HSCT aircraft in the operational fleet is a factor, projected levels of ozone loss are shown for fleet sizes of 500 and 1000 airplanes. The chart shows predictions of ozone depletion for EI's of 5 and 10. At the anticipated fleet size of 1000 units, the EI index of 10 produces unacceptable ozone loss levels. Based on these results, the combustor emissions design goal was established at an index of 5.

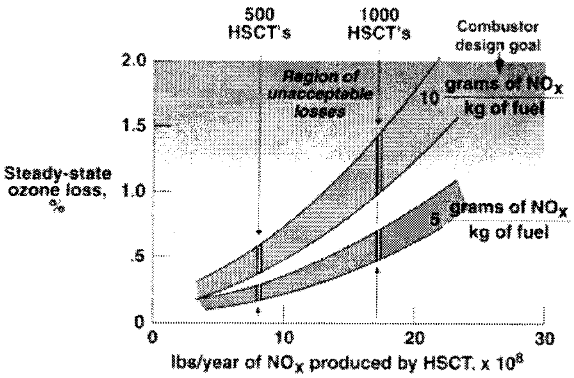

Figure 6- Potential ozone loss from HSCT fleet.

Combustor. Exhaust emissions are generated during the fuel burn process in the combustor. The higher temperatures required of an HSCT engine would increase the levels of NO_x emissions. The Concorde is reported to have a NO_x emissions index around 20, and for an HSCT with a similar combustor design, the value of EI would be driven to 35 or 40.

Key to achieving ultra-low levels of NO_x is uniform burning that occurs sufficiently away from stoichiometric conditions---conditions with the exact amount of oxygen needed to complete the combustion process. Burning at stoichiometric conditions results in high temperatures and increased NO_x production, as shown in Fig. 7. In the current HSR program, two combustor design concepts are under consideration: the Rich-burn Quick-quench Lean-burn (RQL) and the Lean-Premixed-Prevaporized (LPP).

The RQL, shown in Fig. 8, is a two-stage combustor. It reduces the formation of NO_x by first burning under fuel-rich conditions where all the oxygen

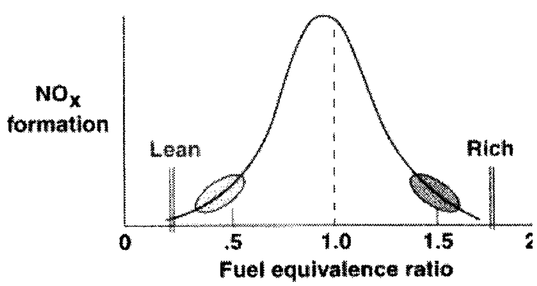

Figure 7 - Low NO_x combustor design philosophy.

present reacts with the fuel and not with the nitrogen in the air to form NO_x. The second step introduces the remaining air and rapidly mixes it with the products of the first stage. In this way, the process is completed in an excess air environment and at a low enough temperature that reduces NO_x formation.

The LPP reduces the formation of NO_x by vaporizing and mixing the fuel and air before combustion under excess air conditions. This reduces the possibility of localized regions of high temperature and thus reduces NOx formation.

Both concepts have been tested at lab scale in the flame tube laboratory at NASA Lewis Research Center, and the results were well within desirable limits of

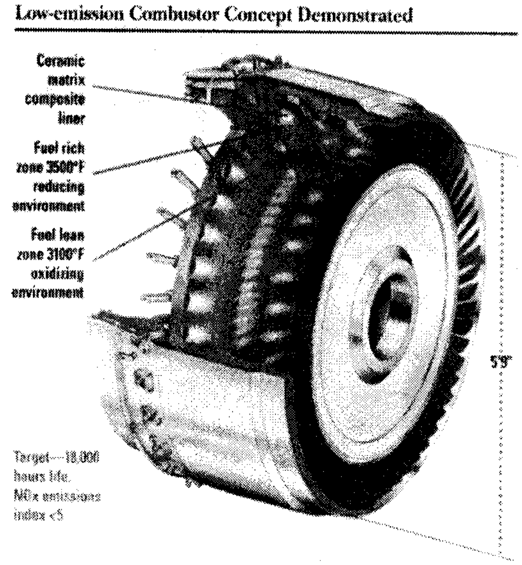

Figure 8 - Low emission combustor concept.

NO_x. At sector scale (one-fifth of full scale), initial results showed large variations in EI, but as test techniques were refined, EI levels were within acceptable limits.

For both combustor concepts, liner material is a challenge because active cooling with air changes the mixing and chemistry that are critical for low NO_x. Thus, ceramic matrix composites (Fig. 9) are the leading candidate materials for the 3500°F environment and 9000-hour life requirements. These composites have been demonstrated at design temperature and near mechanical load conditions using accelerated test techniques. The combustor concept will be downselected this year, and a full-scale annular combustor with the selected liner material will be tested for final technology demonstration.

Characterizing engine exhaust is a highly coupled

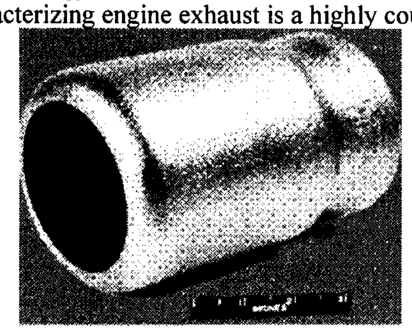

Figure 9 - Ceramic Matrix Composite (CMC) liner for low NO_x combustor.

process. Trace species can undergo significant change downstream of the combustor; therefore, turbine and exhaust nozzle processes must be included as a critical part of the determination of atmospheric impact.

Emission Standards. The only emission standards that currently exist for supersonic aircraft apply to the landing-takeoff cycle (International Civil Aviation Organization (ICAO) Annex 16). No cruise emission standard for supersonic or any other aircraft currently exists. The path to such a rule is not yet well defined. In general, these two steps are likely:

–An international assessment of the ozone impact of an HSCT fleet conducted by the United Nations Environmental Program (UNEP) and the World Meteorological Organization (WMO), with support from NASA, NOAA, and other federal agencies around the world. The climate impact will be assessed by the Intergovernmental Panel on Climate Change (IPCC) in parallel with the UNEP/WMO assessment.

–The development of a supersonic cruise emission standard by the ICAO Committee on Aviation Environmental Protection (CAEP) with implementation in the United States by the Federal Aviation Administration (FAA) and in Europe by the JAA (Joint Aviation Authority).

Preliminary discussions of a supersonic cruise emission standard was begun in early 1977 within the ICAO-CAEP Working Group 3 on emissions. The focus was on the development of rule criteria and not on rule options. In the United States both the FAA and the Environmental Protection Agency (EPA) will be involved in the emissions rulemaking process. The EPA is responsible for promulgating new aircraft emissions standards under the Clean Air Act, while the FAA is responsible for implementing them through Federal Aviation Regulations (FAR).

3.3 Noise. Community noise is a dominant constraint in the selection of the HSCT engine cycle and airframe designs. Because future supersonic airplanes will operate from existing international airports, they must meet local airport community noise requirements and noise certification regulations similar to those for subsonic airlines, which are established in the United States through the FAR. Any transport airplane introduced early in the 21st Century must meet noise criteria established by FAR 36 Stage 3, where stage refers to successive levels of increased noise stringency. Because of successes in reducing noise levels in the newer subsonic engines and continued crowding around airports, Stage 4 could be imposed shortly after the turn of the century.

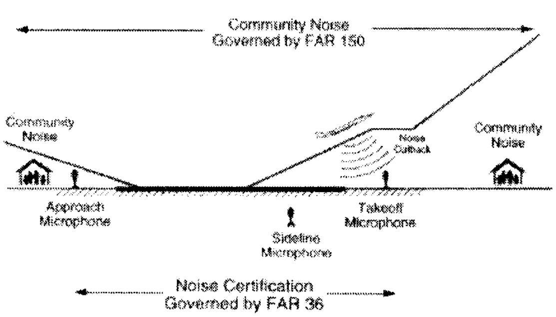

Figure 10 - Certification Measuring Points.

Noise regulations governed by FAR 36 Stage 3 require certain measurements for approach noise, sideline noise and takeoff noise as shown in Fig. 10. Acceptance by the surrounding community may depend on noise levels that match those generated by subsonic transports as shown in Fig. 11. The figure shown noise level reduction trends for subsonic jets since 1960. As shown, the Concorde, which continues to operate on noise waivers with its Olympus turbojet

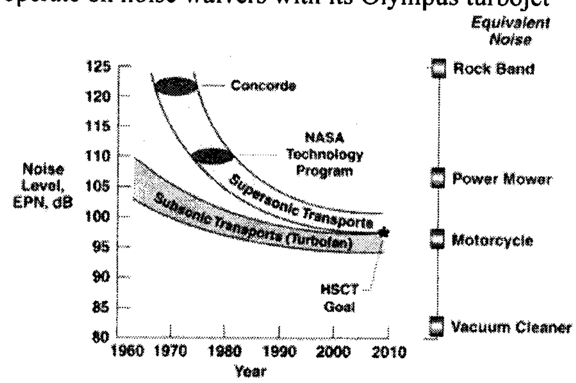

Figure 11- HSCT noise reduction challenge.

engines, far exceeds the noise levels of its subsonic counterparts. To accommodate regulations and to anticipate progress, noise goals for the HSR Program have been established as -1, -5, -1 or 1 dB below the Stage 3 sideline noise limit, 5 dB's below the Stage 3 takeoff noise limit, and 1 dB below the approach noise limit.

The strategy for the HSCT noise footprint is to stay within the same bounds as subsonic transports operating from the same airport. The FAA guide for community noise determines possible impact for new

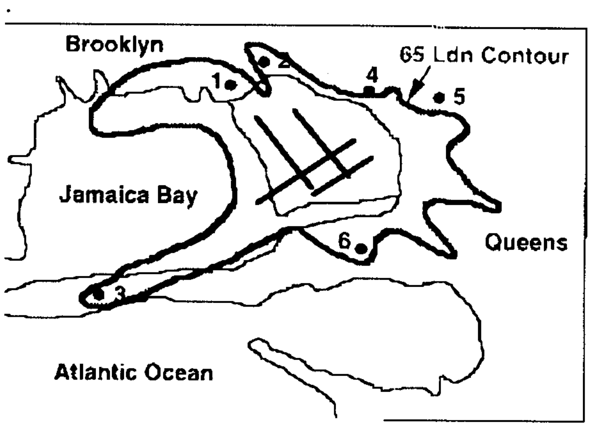

Figure 12- Airport noise compatibility.

aircraft types by employing a metric which generates noise contours from airport operations data (Ldn = Level day-night). The guideline asserts that if the proposed action would result in greater than a 17 percent increase in the 65 Ldn contour area, then further study of the proposal is imposed. Shown in Fig. 12 is the 65 Ldn contour surrounding John F. Kennedy airport in New York.

Noise Reduction. HSCT noise reduction is a classical aircraft systems problem with highly coupled components; for example, the nozzle noise suppression effectiveness is dependent upon the flow conditions presented by the engine. Noise reduction strategies involve design innovation for most of the engine/nacelle components—fan, inlet, core and nozzle. Before the propulsion system can be optimized for noise reduction (and performance), the designer must understand and properly characterize the noise sources associated with the propulsion system components. A simplified illustration of these noise sources is presented in Fig. 13 for the low bypass ratio engine applicable to supersonic transports and, in comparison, for the high bypass ratio engines typically employed on today's subsonic jets. The shape of the source noise envelope is representative of the magnitude and direction of the acoustic radiation pattern. With proper engine design and integration with the configuration jet shock noise will be minimized. The dominant noise source contribution for supersonic propulsion is the jet mixing noise which will be addressed below. Turbomachinery noise sources from the compressor, fan and turbine will play a contributing role in the approach condition. There are other noise sources such as airframe and combustor noise which play a lessor role and are not a major part of the HSR technology development.

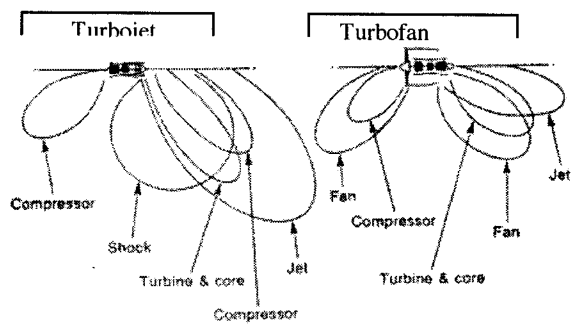

Figure 13- Noise sources.

Achieving the required noise reduction without undue loss in engine performance continues to be a major challenge in the propulsion program.[5] Exhaust jet noise is directly related to the velocity of the gases coming out of the exhaust nozzle. If the velocity of the gases is reduced, the jet noise is also reduced. The exhaust speed can be reduced by lowering the temperature of the exhaust gases by mixing them with ambient air during takeoff. The mixed-flow turbofan cycle has been selected for the HSR technology development. Although this cycle has a moderate bypass ratio to slow the jet flow, a mixer-ejector nozzle must also be included to provide most of the jet noise reduction. The nozzle entrains outside freestream air and mixes it with the hot-core jet. This process reduces noise by approximately 16 dB. During supersonic cruise, external air entrainment is not required, so the ejector doors are closed to eliminate this source of drag. Small-scale nozzle wind-tunnel tests of the current HSCT nozzle design concept have demonstrated the projected level of noise attenuation while still meeting performance requirements. To keep nozzle weight at a minimum, advanced materials are being developed. These include thin wall castings of superalloys for the mixer, gamma titanium aluminides for the flaps, ceramic matrix composite acoustic tiles for reducing mixing noise, and thermal blankets to protect the nozzle backside materials.

As discussed in the previous section, the noise reduction challenge requires that the HSCT produce takeoff noise levels that are 5 dB below certification requirements in order to provide compatibility with subsonic transports under the takeoff flight path. HSR study results have indicated that the solution may demand contributions to noise reduction beyond the propulsion system. An efficient high-lift reduces the demands on engine thrust during the low-speed flight of takeoff, climbout and landing. Shown in Fig. 14 is an HSR high-lift concept being tested in a NASA low-speed wind tunnel.

Figure 14- High-lift wind tunnel tests.

The noise problems of the HSCT are exaggerated because of the low aspect ratio planform which provides optimum performance at high speed. In addition to engine cycle, nozzle and high-lift systems which are used to achieve the noise goals, the designer also has the option of oversizing the engine and then reducing the jet velocity at takeoff. The penalty with this approach is the tremendous weight growth of the engine which moves the airplane into a region of unacceptable economics. The most effective strategy for achieving an

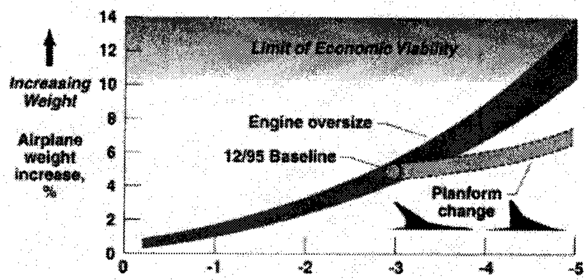

Figure 15 - Weight increase from noise reduction strategies.

additional noise reduction increment for the HSR baseline configuration was to increase low-speed aerodynamic performance by a change in airplane wing aspect ratio. The band in Fig. 15 shows the dramatic change in the weight trend for achieving the noise goal through planform change as compared to the engine oversize option.

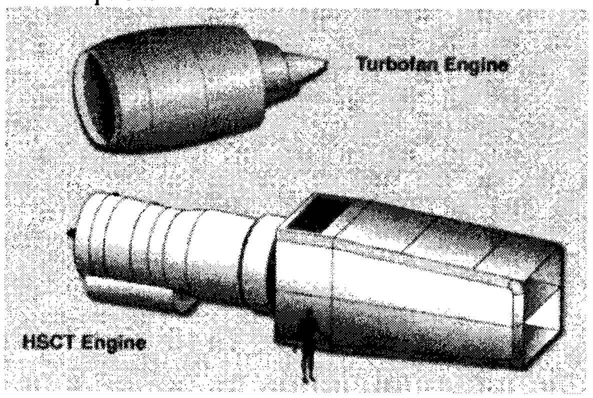

Figure 16- Comparison of turbofan and HSCT engines.

Because of the conflicting demands on the HSCT propulsion system---increased thrust, efficient high-speed operation, and reduced noise---the resulting system being considered is more than twice as large as the current subsonic systems and nearly three times larger than current military supersonic engines. Shown in Fig. 16 is a schematic showing a comparison of the

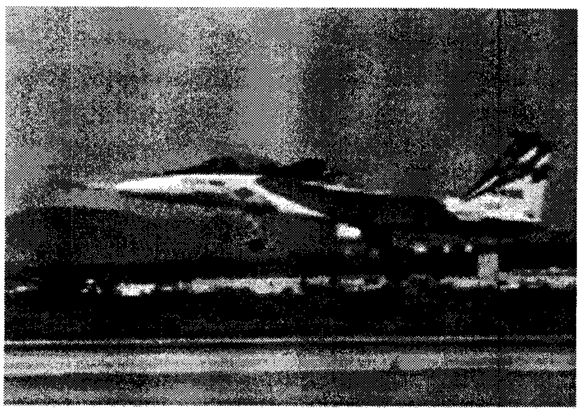

Figure 17 - F15 used in noise prediction tests shown landing

turbofan and the proposed HSCT engine.

Noise Prediction Methods. As with any advanced technology development program, a major component of the HSR program is the development and validation of the prediction tools. For noise prediction, each of the HSCT noise sources identified in Fig. 13 must be modeled and incorporated into an executive routine to calculate total configuration noise levels. Individual source routines require substantiating data for calibration and validation.

A flight test program was conducted at the NASA Dryden Flight Research Center using a modified F-15 (Fig. 17) to generate data for calibration of climb-to-cruise acoustic prediction methods (Fig. 18). The need for the calibration is evidenced by the large discrepancies in predictions made using the two

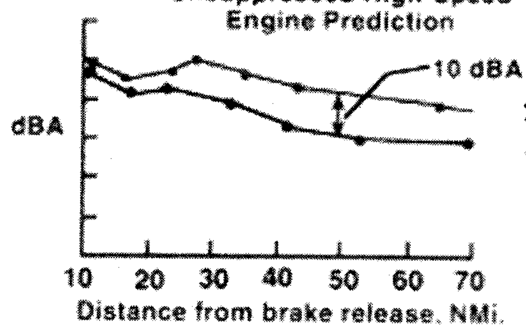

Figure 18 - Noise prediction variation.

available codes which predicted noise at distances up to 70 miles from brake release.

3.4 Sonic Boom. The sonic-boom pressure field which accompanies any airplane during the supersonic portion of its flight presents a formidable problem for researchers. A schematic of a sonic-boom pressure field is shown in Fig. 19. Results of the early feasibility studies showed that the viability of a supersonic transport would be increased by several factors if the

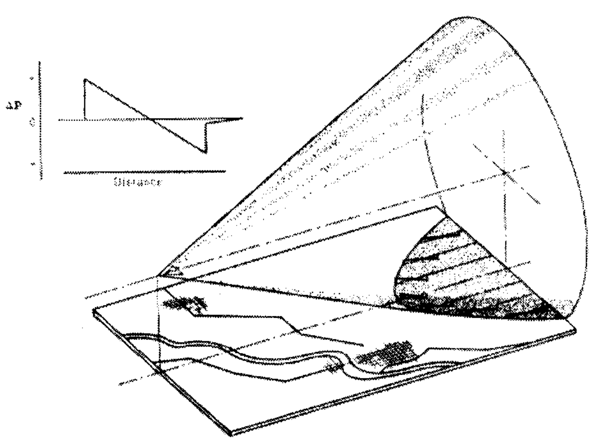

Figure 19. - Sonic-boom pressure field.

environmental constraints which prohibit overland supersonic flight could be removed. Although current projections indicate that the HSCT could be economically successful if it flies supersonically only over water, the economic benefit would be increased if the sonic boom of the HSCT could be reduced to a level acceptable to low-populated corridors, and significantly increased if unlimited overland supersonic flight were possible.

The bow shock of the Concorde is approximately 2.0 psf---a level which is not acceptable for overland flight. Because it is not known what level, if any, is acceptable, early work in the HSR sonic boom element included acceptability.[6] Research areas included: (1) sonic boom prediction; (2) configuration design and operation to minimize the sonic boom; (3) human acceptability studies using minimized signatures; and (4) atmospheric effects on the sonic boom signatures.

An illustration of the impact of the aerodynamic shape on an airplane's sonic boom is shown in Fig. 20. Typically, the optimum aerodynamic designs have smaller, highly-loaded wings while the low-boom designs tend toward larger, more lightly-loaded wing surfaces.

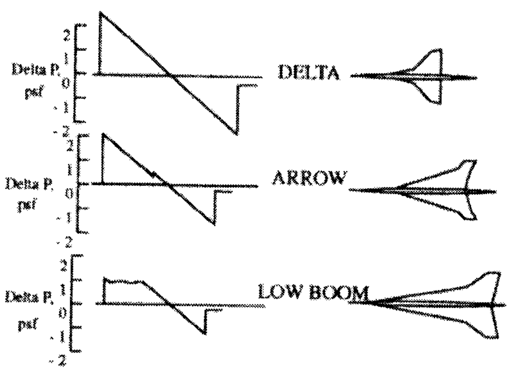

Figure 20 - Low-boom shaping concepts.

Though sonic booms have typically been defined by the level of their bow shocks, with the advent of shaped signatures it was found that there were significant pressure signature features which were not captured by the bow shock. Perceived loudness in decibels (PLdB) has been suggested by acousticians to be a better measure of sonic boom disturbance when not dealing with N waves.

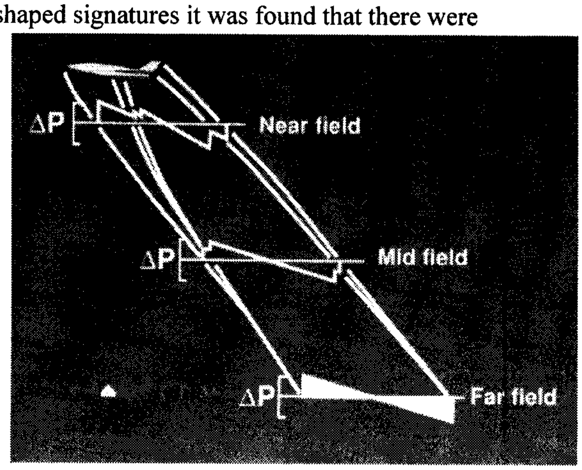

Figure 21 - Sonic-boom propagation.

Shown in Fig. 21 is a typical propagation of shocks from an airplane to the ground sonic boom signature. It is evident that to correctly predict the signature on the ground, one must accurately predict the shocks generated at the airplane and their coalescence pattern during propagation.

Figure 22- Flow field of Mach 3 low-boom concept.

Prediction Methods. During the current HSR program, shock patterns near the aircraft have been predicted by higher order Euler computational methods[7,8] rather than with the linear theory methods used during the sonic boom studies of the 1960's. Shown in Fig. 22 is the flow field generated by an Euler code for a low-boom Mach 3 wing-body concept. The flow-field shown is one body length behind the aircraft. Clearly evident in this figure are the high pressure areas of the bow shock and the shocks from the wings. The lower pressure area directly beneath the aircraft is indicated.

As methods for predicting near-field shocks gained precision, the need to calibrate propagation methods increased. Data to calibrate these methods were collected from a flight test conducted at the NASA Dryden Flight Research Center in 1994. This test included the advantage of having propulsion exhausts in the results. An SR-71 was flown at supersonic Mach numbers and its shock structure at several distances from the airplane was probed by an F16XL with the measuring probe attached to its nose boom. Data collected in this manner was used to calibrate both the CFD nearfield predictions and propagation methods which predicted the shock structure at greater distances from the aircraft. Shown in Fig. 23 are an artist's enhanced photograph of the F16XL underneath the

SR71 and a comparison of the CFD predicted pressure signature with that measured using the F16XL.

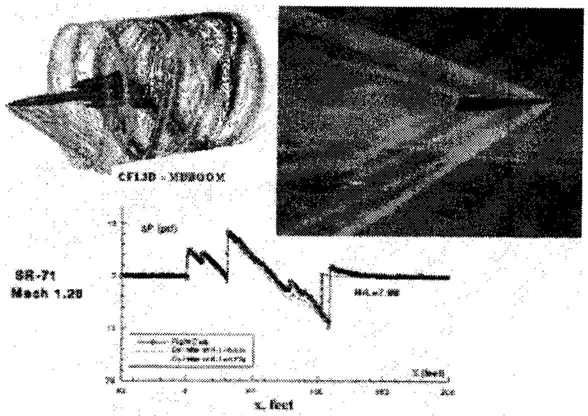

Figure 23 - Tests to calibrate CFD and propagation.

Atmospheric Effects. Thousands of sonic-boom pressure signatures from aircraft were measured in the 1960's. Analysis of these signatures indicated that the atmosphere can have large effects on the ground

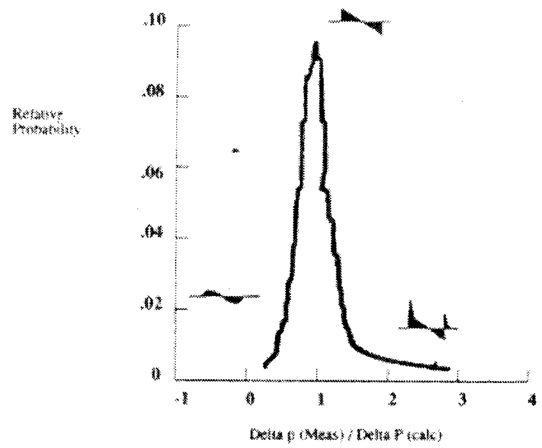

Figure 24 - Statistical distribution of measured sonic-boom pressure signatures. (Ref. 7)

signature. Shown in Fig. 24. is a plot showing the probability that the measured signature will be less than, equal to, or greater than the predicted signature. Though the majority of the signatures were near the predicted values (ΔP meas/ΔP calc = 1), there is a wide variation in shock values. Signatures which have long rise times, such as those shown on the left, are less disturbing to the observer. Shocks which become peaked, such as those shown on the right, can result in noise levels several times larger than the nominal. Additional flight tests were conducted at White Sands Missile Range in New Mexico in 1994 to develop correlations between turbulence levels and the statistical distribution of the measured signatures.

Human Acceptability. To develop data on the human acceptability of sonic boom, tests were conducted in a computer-driven sonic boom simulator, using in-home sonic boom players, and in field studies. The sonic-boom simulator is shown in Fig. 25 and the in-home system is shown in Fig. 26.

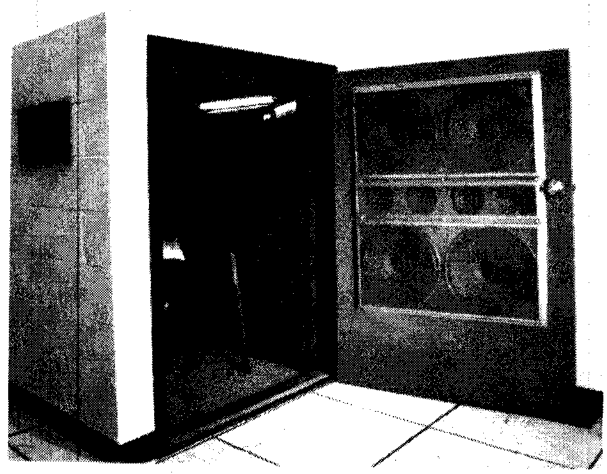

Figure 25 - Sonic-boom simulator.

Both systems played computer generated sonic booms of various strengths and of the n-wave and the shaped variety. Human respondants were asked to give their levels of annoyance with the sonic booms. Results from both tests were quite promising in that there was a definite benefit shown in the response to the shaped signatures.

The third phase of the human acceptability studies consisted of surveys of persons who had routinely been subjected to sonic booms over a period of years because of their proximity to military operational areas. Fig. 27 contains a prediction of human annoyance based on a National Research Council study of continuous noise. Their guideline predicts that approximately 10% of the population would be annoyed at a noise level of 60 dB. The results of the HSR survey showed that nearly 35% of the population would be annoyed at this sonic boom level.

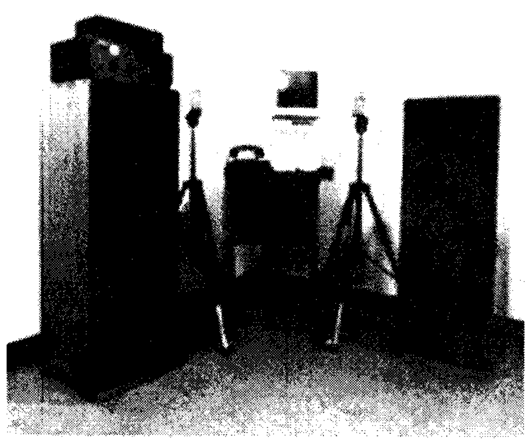

Figure 26 - In-home sonic boom system.

When the results of these surveys became known, the risk of altering the HSCT design to achieve overland flight was perceived to be higher than acceptable. Thus, the sonic-boom minimization efforts of the HSR program were terminated and the acceptability studies refocused on marine mammal

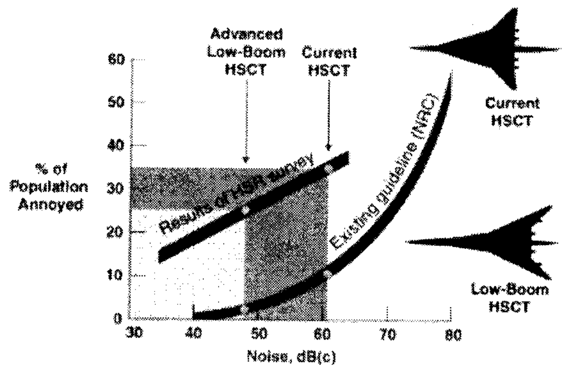

Figure 27- Human response to sonic booms.

concerns. Studies were initiated with marine mammal experts to ensure that any sonic-boom impact to these protected species would be minimal[5].

In response to U.S. policies detailed in the Marine Mammal Protection Act and the Endangered Species Act, research on marine mammal behavioral response to sonic booms is being conducted. The National Zoo and Hubb's Research Institute are conducting studies of the wildlife response to sonic boom events and levels. In previous studies, biologists have shown that wildlife will quickly habituate to the booms. These results are also shown by anecdotal experiences such as the use of air cannons in Chesapeake Bay to frighten sea gulls away when fishing nets are pulled in, and of underwater explosions near the Ballard Locks in Seattle to discourage sea lions from eating the steelhead salmon on their way to spawn. Ironically, these devices soon become the 'dinner bell' for these flocks and herds[4].

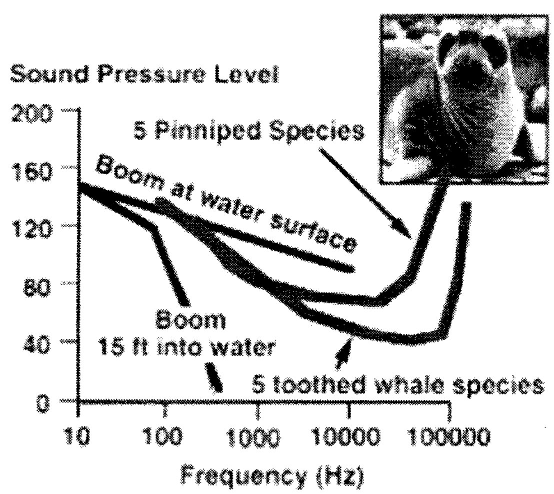

Figure 28 - Sonic-boom underwater levels.

Another concern is noises that may affect marine mammals by interfering with their ability to detect calls from other members of their species. Numerous studies have already examined the effects of noise from human activities including ship propellers, underwater drilling for oil and gas recovery, and offshore construction operations. Calculations indicate that the high frequency component of the sonic-boom signature has virtually disappeared by 15 feet of depth and thus that there would be minimal underwater sonic boom impact on any marine mammals (See Fig. 28).

4 ECONOMIC VIABILITY

In addition to the environmental constraints on the HSCT which require technology advances, additional technology advances are required to make such a vehicle economically viable. The airframer must be able to spread developmental costs over 500-1000 aircraft to recover costs and make a profit. The airlines must be able to afford the acquisition and operational costs while charging passengers a minimal surcharge over nominal subsonic fares. The $8000 round-trip fare from New York to London on the Concorde has limited that airplane to only the very rich, thus also limiting the number of units sold. Developmental costs for the Concorde have never been recovered. Thus, though it has received accolades as a technological feat---flying for over 20 years without incident---its economics remains wanting.

To achieve economic viability, the strategy of the HSR Program is to increase productivity by increasing the passenger load to three times that of the Concorde, increasing the range to enable non-stop flight across the Pacific, and adopting a cruise Mach number that allows two daily non-stop flights across the Pacific. These goals should be accomplished at a total weight which would allow economic operation of the aircraft---projected to be 700,000 to 800,000 lbs. In addition to an efficient propulsion system which meets all environmental goals, technology goals of the HSR program include: improved lift at low speed and cruise; reduced drag, lightweight, durable materials and structures, and an advanced flight deck with an external vision system.

4.1 Aerodynamics. The stated objectives of the HSR Aerodynamics area are to generate design methods which improve cruise L/D by 1/3 over the Concorde, to optimize the high lift system, and to provide acceptable stability and control and ride quality features. To accomplish these objectives, work is continuing in the development of analytical methods and design techniques.

State-of-the-art CFD methods have been coupled with optimization techniques that adjust wing, fuselage, nacelle, and empennage geometry to reduce supersonic drag by over 10 percent relative to designs optimized using linear methods (See Fig. 29). These algorithms are now being extended to include multi-point

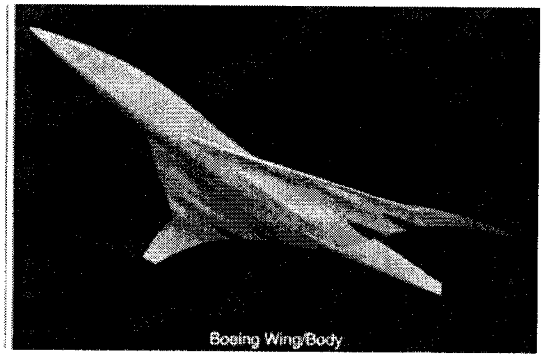

Figure 29 - Optimized HSR Technology Concept.

optimization to accommodate the reference mission of 85 percent supersonic and 15 percent subsonic.

Optimized designs are built and tested in NASA supersonic tunnels to validate the predicted performance. A 1.7 percent model of the HSR Technology Concept is shown in Fig. 30. Methods for predicting aeroelastic effects of models under load are

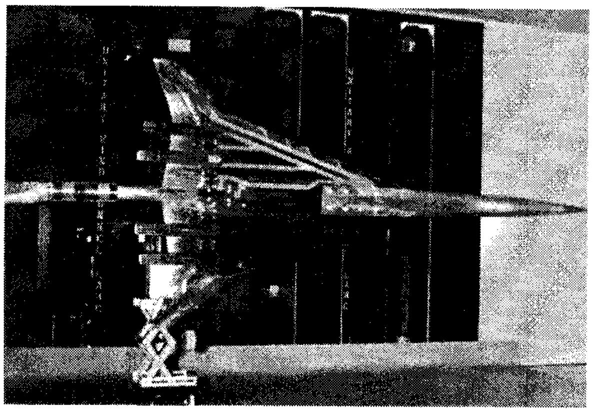

Figure 30 - 1.7% model of the HSR Technology Concept Model.

also being developed and validated in wind tunnels at NASA Langley and at NASA Ames.

Another concept for achieving high-speed drag reduction is laminar flow control[4]. During a flight test

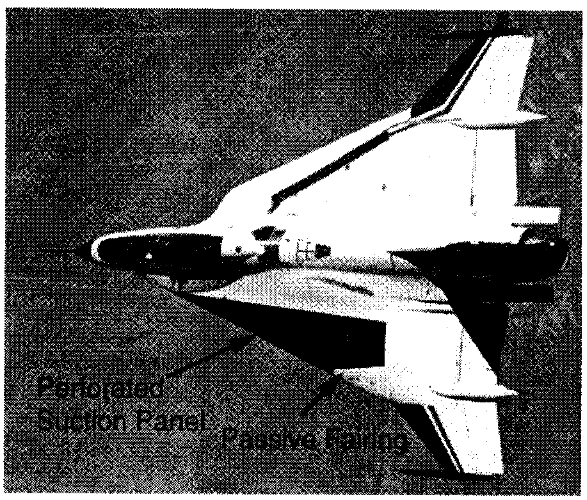

Figure 31 - F16XL fit with laminar flow glove.

program at NASA Dryden earlier in the HSR Program, significant drag reductions were demonstrated at Mach 2.0 on an F16XL which had been fitted with a laminar flow glove (See Fig. 31). Ten million laser-cut holes in the left-wing glove permitted a suction system to control the laminar boundary layer and prevent its transition to a turbulent layer where drag levels are higher. Though this flight test was successful and there is a potential for large drag reductions in supersonic laminar flow control (SLFC), this element is no longer a part of the HSR program because further demonstrations are needed.

4.2 Structures and Materials. At a cruise Mach number of 2.4, the aluminum structure used by the Concorde is no longer feasible due to skin equilibrium temperatures which exceed 350°F in several sections (Fig. 32).

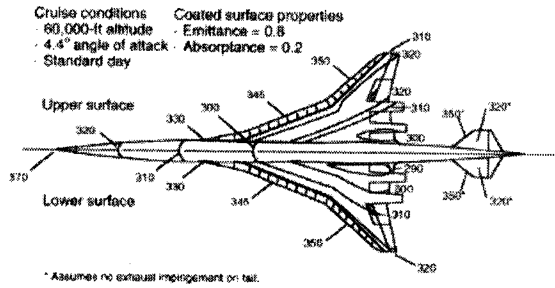

Figure 32 - Skin equilibrium temperatures at 60,000 ft and Mach 2.4.

An airframe of titanium alloys, which would meet temperature requirements, exceeds the weight requirements for an economic vehicle. These conflicting requirements place major challenges on the materials and structures engineers to develop new advanced materials which do withstand the required temperatures, are shown to be durable up to the required 60,000 hours, are lightweight and damage tolerant, and have the desirable aeroelastic characteristics.

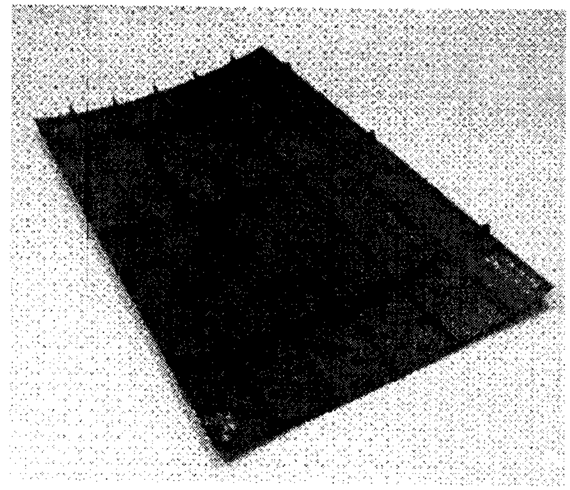

Figure 33- Curved PETI-5 composite skin-stringer panel.

For the current HSR Technology concept, material fabricated from PETI-5, a lightweight composite resin developed at NASA, holds promise. PETI-5 coupons have been subjected to 15,000 hrs of thermo-mechanical fatigue tests without any degradation of properties. A similar material, K3B has been tested up to 40,000 hrs. in isothermal tests (350°F for 4.5 hours).

Honeycomb sandwich and skin-stringer panels, both flat and curved, are being fabricated of PETI-5 and subjected to structural loads tests. Using a building block approach, as the program progresses and downselects are made, larger components will be fabricated using PETI-5 and tested in facilities such as the Combined Loads Test Facility (COLTS) shown in Fig. 34. In COLTS, fuselage sections are subjected to a combination of loads that would be seen in actual flight.

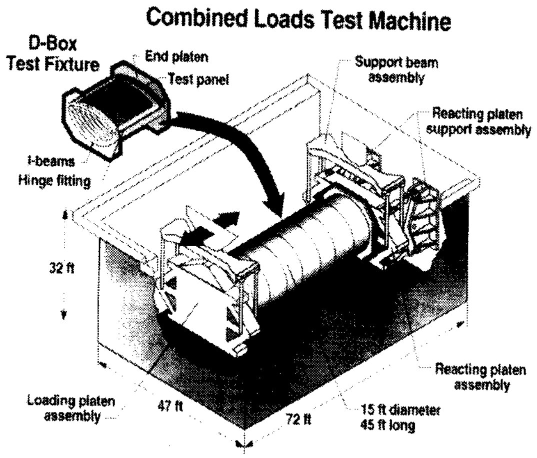

Figure 34 - COLTS Facility at NASA LaRC.

4.3 Flight Deck. To further save weight in the HSCT, the HSR program is considering an external vision concept rather than the variable-geometry drooping nose and retracting windshield visor of the Anglo/French Concorde. There will be no forward windows, only side windows. Engineers are investigating the technologies necessary to provide artificial forward vision. One idea being considered is to mount video cameras on the landing gear and vertical tail to provide a panoramic forward view in the cockpit display. The display would be overlaid with symbols; and altitude, attitude and speed information would be provided. For landing, the symbols would include goal posts to aid runway alignment.

During night and low-visibility operations, the aircraft would be equipped with dynamic-range video sensors augmented by X-band radars to detect obstacles. A further aid would be a differential global positioning system database which would provide on the screen flight profile information and drawings of major airports' runways. Researchers estimate that in excess of 10,000 lbs. would be saved with the elimination of the droop nose[10].

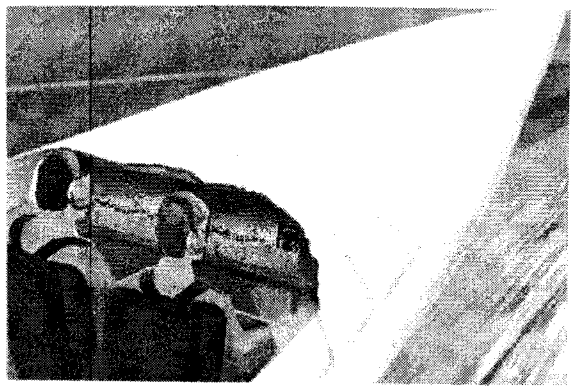

Figure 35 - Conceptual HSCT flight deck.

Using the NASA Boeing 737 research aircraft, the external vision concept has been shown viable by over 200 takeoffs and landings with the pilot in control using a second research cockpit which was behind the regular cockpit (see Fig. 36).

Engineers continue to address issues such as camera vibration, pilot integration of the flat panel display with the side window view, and ground operations.

Figure 36 - Pilot at B737 research flight deck.

5 Tu-144LL FLIGHT EXPERIMENTS

In September 1994 a joint NASA/U.S. Industry program to conduct flight tests using the Tupelov Tu-144 was initiated. Management and technical teams from NASA and Boeing worked with IBP Aircraft Ltd. (the Tupelov agent) and the Tupelov Design Bureau, the owner of the Aircraft in planning the refurbishment and re-engining of the Tu-144, and the implementation of two ground engine tests and six flight experiments. The original Koliesov engines were removed and replaced with NK-321 augmented-turbofan engines, which were originally produced for the Tupolev Tu-160 Blackjack bomber. A new digital data system (Damien PCM) was also installed to collect airworthiness data and data from the experiments. Thermocouples, pressure sensors, microphones, and skin friction gauges were placed on the airplane to measure the aerodynamic boundary layer.

The Program was conducted in three phases. Phase I, the aircraft modification and refurbishment was culminated with the first flight of the modified vehicle, the Tu-144LL, in November 1996. Phase II consisted of the flight test planning and the installation of the instrumentation and data acquisition system on the test aircraft; and Phase III, the conduct of the flight experiments and the acquisition of data, was accomplished during the 19 flights to establish the airworthiness of the Tu-144LL over the entire flight envelop. Data from the tests were received, translated into engineering units and distributed to the NASA/Industry user community by engineers at NASA Dryden.

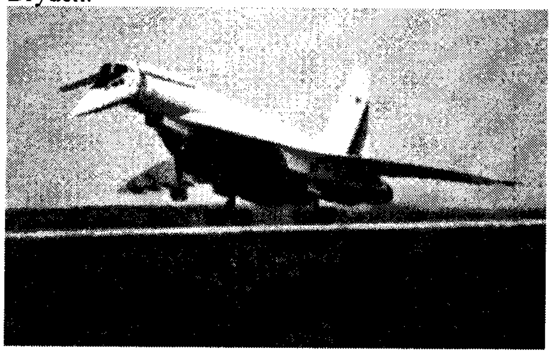

Figure 37 - The Tu-144LL landing in Russia.

The ground test engine experiments were:
(1) Engine operation behind close coupled structures
(2) Engine face reflection properties
The flight experiments conducted were:
(1) Surface/Structure Equilibrium Temperatures
(2) Propulsion System Thermal Environment
(3) Slender Wing Ground Effects.
(4) Structure/Cabin Noise.
(5) Handling Qualities Assessment.
(6) C_p, C_f and Boundary Layer Measurements.
Data from these tests will primarily be used to calibrate numerical models and simulation studies used in the design and development of the HSCT.

Because of the success of the flight test program, a follow-on program is currently being planned for late 1998 and the first half of 1999.

CONCLUDING REMARKS

NASA works with partnership with the American airframe and propulsion industries in developing the technologies needed for an HSCT. Though the challenges are formidable, they are not insurmountable. The Technology Configuration (Fig. 38), which has been used in the NASA HSR Program, is a convenient instrument for assessing and making decisions on technologies, but it is not an airplane designed by the American industry. Armed with these technologies developed in the HSR program, the decision to launch the HSCT and the final design will be that of industry.

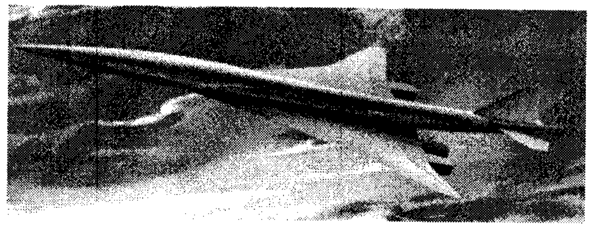

Figure 38-Artist's drawing of NASA's High-Speed Technology Concept.

ACKNOWLEDGMENTS

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