AN OVERVIEW OF NASA'S HIGH-SPEED RESEARCH PROGRAM

Dr. Alan W.Wilhite
Director, Systems Management Office
NASA Langley Research Center

Dr. Robert J. Shaw
Director, Ultra-Efficient Engine Technology Program
NASA Lewis Research Center

Abstract

The National Aeronautics and Space Administration sponsored a joint High-Speed Research Program with United States airframe and propulsion companies to provide the critical high-risk technologies for a Mach 2.4, 300 passenger civil transport. Laboratory and medium-scale tests provided promising results in meeting both the environmental and economic goals for a future High-Speed Civil Transport. However, before the technologies were demonstrated at large and full scale, the program was cancelled because of global economic concerns of the U.S. transport industry.

1 Introduction

The U.S. initially dominated the world's civil jet transport market, but over the past 15 years the European Airbus Industrie has been eating into the U.S. market share. In the past few years, Airbus has captured half of the civil large transport market share. The Europeans are continuing the offensive with a very large transport (>500 passengers) on the drawing board and the development of technologies for a second generation Concorde. Although the Concorde was not an overwhelming financial success for the manufacturers, it was a technological and systems integration marvel for its time and provided the confidence and foundation for the formulation of the multi-nation Airbus Industrie. Airbus was formed in 1970, one year after the initial flight of the prototype Concorde.

The U.S. industry has shelved the plans for megaliners stating a lack of market for that size airplane; however, they were keenly interested in a more productive, mid-size (300 passenger) airliner that could leap frog the current transport industry. Speed is one way in which productivity can be dramatically improved. Compared to a megaliner, a mid-size supersonic airplane can fly the same number of passengers using two round trips while halving passenger travel time and provides more market flexibility with its reduced passenger capacity. A supersonic airplane can be used as a mid-range, large-capacity transport saving over 6 hours from Los Angeles to Tokyo or as a long-range, mid-size transport by using short service stops saving over 10 hours from Los Angeles to Sydney.

Congress cancelled the U.S. Supersonic Transport (SST) program in March 1971. Cancellation justification was based on both environmental and performance issues. Environmentally, many countries outlawed supersonic flight overland because of the sonic boom, thus severely restricting projected market penetration; atmospheric scientists predicted catastrophic reductions of ozone from engine emissions severely restricting fleet size; aircraft regulators wanted the engines that were designed for supersonic flight to meet subsonic noise certification standards; and health officials were concerned about the effects of high-altitude atmospheric radiation. In addition, performance issues that were cited for the cancellation included the need for more efficient lift-to-drag ratio for both subsonic and supersonic flight; sufficient thrust from propulsion at both supersonic and subsonic speeds with low noise and efficient fuel consumption; airframe structures and materials with greater strength with less weight, and system integration techniques to maximize airplane efficiency.

Beginning in 1989, NASA and industry investigated the potential of a High-Speed Civil Transport (HSCT), the airplane specifications, and required technologies. The existing Mach 2 European Concorde and Russian Tu-144 airplanes are not environmentally acceptable or economically viable. The original U.S. SST design was planned for Mach 2.7, but its titanium structure was too heavy. In 1989, the National AeroSpace Plane Program was investing in Mach 25 technology for both Earth-to-Orbit transport and “Orient Express” civil transport applications. At these speeds, the required hydrogen fuel would dictate extreme changes in existing airport infrastructure and the airplane efficiency would be limited because it would rarely see cruising speed with long acceleration and deceleration times required for passenger comfort. The studies concluded that an airplane launched in the early 21st century should be compatible with current airports, use jet fuel, and be within a 10- to 15-year technology reach. Both Boeing and McDonnell Douglas converged on a Mach 2.4, 300 passenger, 5000 nautical mile airplane as a focus for technology development.

Based on the market and technology projections of a HSCT, NASA started the two-phase High-Speed Research (HSR) technology program in 1990 with the civil transport industry -- Boeing, McDonnell Douglas, General Electric and Pratt and Whitney. The $280M Phase I Program focused on the development of technology concepts for environmental compatibility. With the successful completion of Phase I, the $1400M Phase II Program started in 1993. This Phase was to demonstrate the environmental technologies and define and demonstrate selected high-risk technologies for economic viability.

However, because of global economics and the U.S. industry focus on keeping their subsonic market viable, the HSR program was cancelled in 1999. At this point in the program, the technology selections were made for final full- and large-scale demonstrations based on medium-scale ground tests and flight tests. The following is a status report of the program when the program was cancelled.

2 Environmental Compatibility

2.1 Atmospheric Impact and Emission Reduction

The most publicized environmental concern about supersonic flight is the depletion of stratospheric ozone. Dr. Harold Johnston led a group of atmospheric scientists in the SST Congressional hearings of the early 1970s that raised the potential of the significant depletion of the Earth's ozone shield to a global concern.

Ultraviolet rays break down stratospheric ozone into molecular and atomic oxygen. These molecules are later reunited in a reaction that forms new ozone that maintains a sufficient layer to protect the Earth from ultraviolet rays. The currently proposed supersonic transport cruise altitude, where nitrogen oxides (NOx) would be introduced from the engine exhausts, is about 60,000 feet, near the maximum density of stratospheric ozone. These nitrogen oxides, with energy from ultraviolet rays, break down and deplete the amount of ozone by forming molecular oxygen.

The Atmospheric Effects of Stratospheric Aircraft element was formed in Phase I of the

HSR Program to address the ozone issue. An international team of scientists developed global atmospheric models to predict the impact of nitrogen oxides, water vapor, and other exhaust emissions on ozone chemistry and climate change. These 2- and 3-dimensional photochemical transport models were calibrated through laboratory chemical kinetics tests and atmospheric observations. A converted U-2 spy plane called the ER-2 (Figure 1) and balloons provided global coverage to identify photochemical, radiative, and dynamic features of the stratosphere. The ER-2 was also used to sniff the exhaust of the Concorde providing valuable data for near-field atmospheric interactions. As input to these atmospheric models, a global engine exhaust emissions database was defined by city-pair operational scenarios for the HSCT and corresponding flight trajectories between these airports.

Figure 1. ER-2 atmospheric research airplane.

Results from five 2-dimensional atmospheric models showed a range of -0.7 percent to +0.1 percent ozone impact, where positive is creating ozone, based on a mature fleet of 1000 HSCT's flying at Mach 2.4 and a combustor emissions index of 5 grams of NOx per kilogram of fuel burned. These results affirmed the combustor goal of an emissions index of 5 as compared to approximately 20 for the Concorde. Further research enhanced understanding of both chemical and transport mechanisms as recommended by the National Research Council with an emphasis on additional atmospheric observations to assist model validation.

The high level of NOx emissions from current combustors are due to burning fuel near stoichiometric air-to-fuel ratios; the key to reduced combustor emissions is to burn either fuel rich or lean. One concept was a two-stage combustor design called rich burn, quick quench, lean burn design where fuel is initially burned rich, air is then added, and the products are burned lean. The quick air quench mixing with the rich burn products was the challenge. The second concept was the pre-mixed, pre-vaporized lean burn combustor where flame stability and hardware complexity dominated research. Both concepts were tested in flame tube laboratory tests at NASA Glenn Research Center and reduced scale sector tests showing emission indices less than 5 grams NOx per kilogram of fuel at the propulsion industry facilities.

For both combustor concepts, liner material was also a challenge because active cooling with air changes the mixing and chemistry that are critical for low NOx. Thus, ceramic matrix composites was the leading candidate material 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.

2.2 Community Noise

Community noise is the dominant constraint in the selection of engine cycle and airframe configuration designs. Any future supersonic airliner will operate from existing international airports and must meet local airport community noise requirements and national/international noise certification regulations similar to subsonic airliners. Because the HSCT was projected not to operate until after the turn of the century, subsonic noise reduction technologies and the potential for more stringent regulations were being closely followed to formulate the requirements for supersonic technology development. A final conclusion is that any future airplane including the HSCT must be at least as quiet as the fleet average at production start date.

The primary noise source for takeoff is from the high-speed, hot engine jet exhaust. The turbojet cycle used in the Concorde has excellent supersonic performance but also has high noise as opposed to high-bypass-ratio turbofans used by subsonic commercial transports designed for subsonic performance and low noise. A compromise cycle called the mixed-flow turbofan was selected for the HSR technology development. Although this cycle does have a moderate bypass ratio to slow the jet, a mixer-ejector nozzle must also be included to further reduce noise.

This nozzle entrains outside freestream air, which is mixed with the core jet exhaust resulting in a slower and cooler exhaust jet that reduces noise by 16 decibels out of approximately 120. During supersonic cruise, external air entrainment is not required, thus eliminating the drag and reduced efficiency associated with the noise suppression mode. Small-scale wind-tunnel and large-scale (Figure 2) nozzle tests demonstrated the required noise

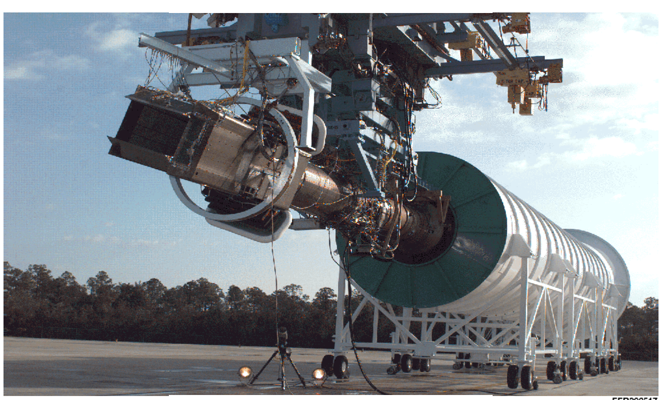

Figure 2. Large-scale nozzle test.

attenuation while meeting performance requirements. To keep nozzle weight at a minimum, advanced materials and manufacturing processes were being developed including thin wall castings of superalloys for the mixer, gamma titanium aluminides for the flap, ceramic matrix composite acoustic tiles for reducing mixing noise, and thermal blankets to protect the nozzle backside materials.

For approach noise where the engines are throttled back and have reduced jet velocity, turbomachinery noise is a key contributor to overall aircraft noise. To address this environmental compatibility challenge, NASA and industry looked at both mixed compression inlet and low-noise fan concepts. Mach 2.4 operation requires a mixed compression inlet for efficient propulsion system operation where the shock structure is managed both externally and internally. Stability, high recovery, and low distortion in the inlet must be balanced with low-noise, operability, and complexity. Two-dimensional bifurcated, axisymmetric translating centerbody, and variable diameter centerbody inlets were being considered. Small-scale wind-tunnel tests, operability tests, and duct spacing ground tests of the Tu-144 engine provided data for the selection, design, and validation testing for performance and operability through the speed regime and approach acoustics.

Additional noise reduction can be attained with high-lift leading and trailing edge wing systems which reduce thrust required for takeoff, climbout, and landing. These advanced high-lift concepts more than double the low-speed lift-to-drag ratio relative to the Concorde when combined with advanced landing and takeoff procedures such as automatic flap and throttle settings.

2.3 Sonic Boom

At supersonic speeds, an aircraft produces shock waves that propagate to the ground, creating sudden pressure changes that may be perceived as a startling and annoying noise. To minimize human disturbance, HSCT supersonic flight will only take place over the oceans.

In response to policies detailed in the U.S. Marine Mammal Protection Act and the U.S. Endangered Species Act, research on marine mammal behavioral response to sonic booms was conducted. The National Zoo and Hubb's Research Institute conducted 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 utilization of air canon in Chesapeake Bay to frighten sea gulls away when pulling in the fishing nets and underwater explosions near the Ballard Locks in Seattle to discourage Hershel the sea lion from eating the steelhead salmon on their way to spawn. Unfortunately, these devices soon became the "dinner bell" for Hershel and his buddies.

Other concerns were the noises introduced into the oceans that may affect marine mammal behavior by interfering with ability to detect calls from members of their own species. Numerous studies have already been performed to examine the effects of noise from human activities including ship props, underwater drilling for oil and gas recovery, and offshore construction operations. Because a major part of the energy associated with the HSCT sonic boom would be deflected off the ocean's surface, the noise levels and frequency spectrum generated by these marine sources are potentially much more detrimental to underwater marine life than sonic boom phenomena.

Sonic boom research was initially directed toward reducing boom pressure signature to acceptable levels for flight over land by maximizing the distribution of lift over the airframe. Configurations were designed by computational fluid dynamics methods that were validated for the prediction of the near-field pressure field and boom propagation through the atmosphere with wind tunnel tests and flight and ground measurements of the SR-71 Blackbird. Significant reductions of booms were accomplished; however, the configurations were so radical that economical viability was precluded. These methods were then used to characterize the boom pressure field for the development of operational requirements to avoid populated islands and establish distances for deceleration to subsonic speeds for overland flights.

2.4 Radiation

High-altitude atmospheric radiation is of galactic or solar origin. Galactic cosmic rays are complex, heavy ions of high energy and penetrate deep into the Earth's atmosphere. Solar cosmic rays are generated by solar flares and are less penetrating, but may be very intense over short periods of time. Secondary neutrons are generated in the atmosphere by both sources and can be biologically damaging depending on the dosage.

At supersonic cruise altitudes, the radiation dose is double that of a subsonic airliner flying at 40,000 ft. But because the trip time is halved, the total trip dosage is approximately the same. The major concern is with the exposure levels of the flight crew, especially pregnant members. Radiation exposure can be managed by crew rotation scheduling based on validated radiation prediction methods and measurement.

Currently, there are substantial uncertainties in the knowledge of the radiation in the upper atmosphere and changes in latitude where radiation is higher at the poles because of the magnetic field of the Earth. The National Council on Radiation Protection and Measurements has identified the critical scientific questions that must be answered to provide a sound scientific basis for atmospheric radiation prediction. An ER-2 was equipped with a suite of instruments provided by an international team for characterizing the radiation environment. The solar minimum environment (maximum radiation) was measured to provide the worst case scenario.

3 Economic Viability

NASA is not building the High-Speed Civil Transport nor developing a prototype airplane. NASA is in partnership with the U.S. Industry to develop the most critical, high-risk technologies as the foundation for the industry design and development of an economically viable HSCT.

3.1 Aerodynamics

Aerodynamic research provided potential concepts and validated analytical design and optimization methods for airplane configuration development and ride quality enhancement. These design methods were used for drag reduction and for predicting aeroelastic stability and control characteristics, which are necessary for the design of safe, controllable, and economically viable HSCT configurations.

State-of-the-art computational fluid dynamics methods were coupled with optimization techniques that adjust wing, fuselage, nacelle, and empennage geometry to reduce drag by over 10 percent relative to optimized linear design methods at supersonic speeds (Figure 3). These methods were extended for multipoint optimization to provide maximum range for the airplane with a reference mission of 85 percent supersonic over water and 15 percent subsonic over land. In addition, methods to predict aeroelastic effects of models under load were developed and validated in supersonic and high-Reynolds-number subsonic wind-tunnel tests at NASA's Langley and Ames Research Centers. Test techniques were improved such as pressure sensitive coatings, Reynolds number scaling, and corrections for model support systems.

Another method to achieve high-speed drag reduction is laminar flow control. Significant drag reductions were demonstrated with supersonic laminar flow control (SLFC) at Mach 2.0 on an F16-XL (Figure 4) at NASA Dryden Flight Research Center.

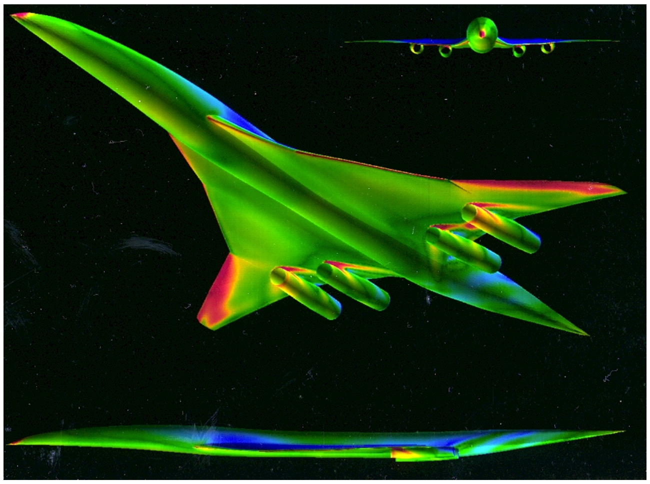

Figure 3. CFD optimization methods using over 400 variables are used for configuration design

Figure 4. Laminar flow control system demonstrated on a F16-XL at Mach 2.0.

Supersonic laminar flow was achieved with a left-wing glove with 10 million laser-cut holes through which a suction system controls the laminar boundary layer to prevent turbulence. Data analyses tools were successfully applied to calculate suction distributions and boundary-layer stability characteristics from flight data.

Supersonic laminar flow control has the potential to improve the aerodynamic performance of the HSCT by 10 percent. This concept was dropped from the program because further technology demonstrations of the subsystems, wing skin with holes through high-temperature composites, and a longer chord demonstration of laminar flow was required to reduce risk for application to a commercial airplane.

High-speed aircraft present unique guidance and flight control challenges. Research in guidance and flight control technology provided a simulation of baseline HSCT airplane dynamics that was used to develop both rigid and elastic airplane control concepts and methods that was applicable to practical HSCT design. Both ground-based and in-flight simulation was used to validate flying qualities criteria and flight control system design criteria. An integrated guidance, control, and display system for safe and efficient HSCT operations in tomorrow's airspace system was developed. Envelope protection strategies and certification criteria were addressed in these systems. Design methods were developed that were used to ensure Level 1 flying qualities and robust performance over the flight envelope for a slender flexible aircraft with both rigid and possibly elastic instabilities.

3.2 Flight Deck

To reduce airplane weight and drag and improve pilot performance and safety, the droop nose with forward cockpit windows may be replaced by large computer-generated displays (Figure 5).

The external vision team, with guidance from the Federal Aviation Administration, defined requirements and technology to provide the functional equivalent of forward sight.

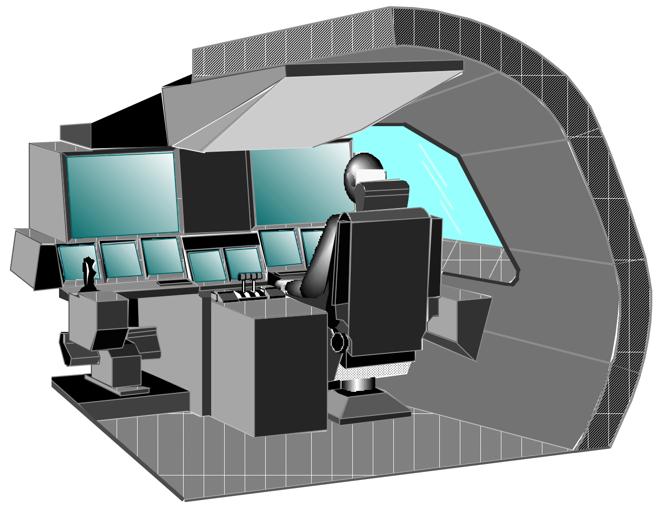

Figure 5. – External vision concept.

During airport maneuvers, video cameras on the nose gear and on top of the vertical tail provide a panoramic view of the runway. Using differential global positioning satellite (GPS) data coupled with a digitized map database of the runways, the pilot can track the current airplane position just like the Pacman video game. After takeoff, the computer overlays the video image with speed, altitude, and any other personalized selected data for the pilot. At cruise, the surveillance system uses the Traffic Collision Avoidance System (TCAS) and radar (to track airplanes without TCAS) to warn the pilot of potential collisions. Also, one version of the navigation system projects a lead airplane, using GPS data and flight profile information, for the pilot to follow. On landing, football goal posts and other symbology aid the pilot for runway line up and a flare indicator is used for touchdown. For night vision, dynamic range video sensors are augmented by X-band radar for object detection. During weather conditions, radar is used to cut through the rain and fog, and the video camera image is replaced with a computer representation of the airport and surrounding topology. The radar data can be processed during airport operations to detect hazards on the runway that cannot be seen, and thus provide greater safety.

A simplified system produced excellent results with a conventional graphic display monitor used by the pilot on the NASA 737 Transport System Research Vehicle that was configured with a second cockpit and had no windows in the middle of the airplane. The final selected system was demonstrated on the ground with the Surface Operations Research Vehicle (Figure 6) and in flight with the Calspan Total In-Flight Simulator (Figure 7).

Figure 6. – Surface operations research vehicle

Figure 7. Calspan Total In-Flight Simulator

3.3 Materials and Structures

The fraction of the operating empty weight for airframe structure is much smaller for a supersonic transport than for conventional subsonic commercial vehicles. This requires the use of innovative structural concepts and advanced materials to satisfy this stringent weight requirement. The operating environment is also more severe because of the high temperatures associated with the aerodynamic friction heating caused by supersonic cruise speeds.

The Mach 2.4 economically viable HSCT drives the materials and structures technology development with a 60,000 hour durability at a cycled 350°F skin temperature and a 30-percent reduction in weight relative to the Concorde. Conventional airplane materials such as aluminum and thermoset composites such as bismaleimides do not have the temperature capability, and titanium alloys are too heavy for the entire airframe. Over 140 different materials were analyzed to downselect to a handful of materials for the enhancement of mechanical properties and fabrication processes.

Titanium was a prime candidate for the main wing box which required high-strength and for the high-temperature-stagnation regions of the aerodynamic surface leading edges. Advanced titanium alloys were developed with a goal of 20-percent improvement in mechanical properties. Major technology challenges included the effects of thermomechanical processing on optimum alloy compositions and the manufacturing processes for reducing costs and risks.

To reduce weight of the fuselage, outboard wing, strake and empennage, polyimide carbon fibers matrix composites (PMC) were developed. A NASA patented polyimide resin called PETI-5 when combined with a vendor produced IM7 fiber demonstrated mechanical properties greater than bismaleimides at 350°F. A "wet" prepreg was developed for laboratory hand layup structures that required long cure times at high pressure in autoclaves to remove the volatiles and was demonstrated in the fabrication of large-scale panels (Figure 8).

Figure 8. Large scale PETI-5 panel

At the end of the program, dry prepreg was being developed that potentially had more affordable manufacturing processes such as resin film infusion and insitu robotic layup.

Durability isothermal tests after 55,000 hours of a PMC showed no degradation, and PETI-5 had over 15,000 hours. Because of the criticality of the durability data, the thermal mechanical fatigue tests were continued after the end of the program.

Summary

NASA's High-Speed Research Program was on track to meet all of the environmental and economic goals established for the program. Technology was demonstrated in medium scale ground tests and flight tests. However, the program was cancelled in 1999 before the large-scale demonstration test articles were developed and tested.