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FORUM

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ABSTRACT

In February 1998 NASA's High Speed Research Program (HSR) was cancelled without fan fare or press announcement. The principal effect of this announcement was to immediately end the research and development that was in progress on the revised supersonic transport or High Speed Civil Transport (HCST) project. This research was to lead to a prototype supersonic transport that would begin flying by the end of the first decade of the 21st Century. The factors for the cancellation of this program were never made clear other than the competing funding of the International Space Station. NASA's budgetary squeeze from the rising cost of the Space Station was and continues to have a negative impact on NASA's aeronautics programs.

This paper discusses the technical objectives of the HSCT research that were in progress at the time and the potential for breakthroughs in several areas that would have made a nationally funded prototype supersonic transport a possibility.

HIGH SPEED RESEARCH

Speaking to the U.S. Air Force Academy graduating class of 1963, President John F. Kennedy announced the federal government was going to sponsor a supersonic transport to become operational in the U.S. air carrier fleet. Three issues dominated this project. The first was the technological basis for sustaining Mach numbers greater than 2. The design goal was a 300 passenger Mach 2.6 vehicle. In 1963 the only aircraft able to sustain speeds in excess of 1000 knots were a long way from meeting the redundancy and safety requirements demanded of today's airliner. The second issue was that of the environment. Nitrogen Oxide (generically NO_x)[1] emissions were thought to be harmful to the upper atmosphere, but not until sometime later was the effect of the exhaust plume from a turbojet aircraft linked to the "green house" gases and potential damage to the ozone layer. Adding to that were the general issues of "noise pollution" and sonic boom. Even if the aircraft was flying well into the stratosphere, above 30,000 feet, the large footprint of the shock waves from the aircraft was disruptive and annoying to the public. Whether or not damage would occur from the shock wave of a heavy jet traveling at Mach 2 at 50,000 feet, the "possibility" that it might occur could not be ruled out. The final factor was, in many minds, the deciding one. Economically, the airline industry could not foresee making money from an SST. The initial expense for the aircraft was on the order of three or four times the cost of a subsonic wide body jet. In order to make the operation of an SST cost effective, the price per ticket would be exorbitant for the traveling public. During its time in service the Concorde did not turn a profit and the passengers paid ten times more for a trans-Atlantic flight than flying coach in a Boeing 747. (Darden, 1998)

The Supersonic Transport was not the only high speed research program that NASA was developing. When NACA expanded to become the nation's space agency, it was in the middle of a decade-long flight research program using experimental aircraft. The most successful and advanced vehicle of the time was the X-15. This was truly a high speed (hypersonic) vehicle. Next in line wase the SR-71 Mach 3 research vehicle that was loaned to NASA. Nothing filled the gap after the X-15 program ended in 1968. The SR-71 was not cost effective for the Air Force and NASA had difficulty justifying research expenses associated with the operational use it its SR-71s.

In the late 1980s people associated with high-speed flight

[1] Derivatives of Nitrogen and Oxygen combinations

research, both in and out of government, began to ask, "Was technology at the point where a supersonic transport could be a viable means of transportation?" The challenges identified by the SST might be met given time to apply new technology (Rosen, et.al., 1993).

HSCT BIRTH

When the Supersonic Transport was cancelled these problems confronting the practically use of a high-speed commercial aircraft remained unsolved. At the top of the list of concerns were the environmental problems that needed resolution. In 1988 an effort was begun within NASA to fund ongoing research leading to the resolution of these problems and the resurrection of a prototype aircraft. The National Research Council reviewed the list of issues that NASA proposed to work on. The NRC Board on Atmospheric Sciences and Climate listed several areas requiring further study. The first was the HSCT's emissions. In addition to NO_x produced by the engines, the study included sulfur dioxide and particulate carbon. Another requirement listed was the need to study plume/wake processes. In the mid-90s this effort was undertaken using aircraft from Ames Research Center and Langley Research Center. The difficulty of getting data on particulate activity and the exhaust from large jet aircraft was evident from the start. Additionally, flight test work was attempted using one of the two operational SR-71s that NASA had available at Dryden Flight Research Center.

In 1988 NASA Headquarters began the preliminary funding of the feasibility studies that would determine if a new supersonic transport could be put into service. The results of those studies were promising. There were several major technical and two economic issues that had to be examined. In 1990 the High Speed Research Program was begun in NASA. At the time, public awareness of program goals was lost in all the background noise from the return to flight of the Space Shuttle and the new mission to build a space station.

CHALLENGES

The research work began on all fronts with numerous contractors and government entities participating. The amazing aspect of this was the cooperation of a variety of companies that would normally compete against each other to get answers to the questions that had to be addressed before anyone could start to build a new supersonic transport.

A list of those concerns associated with these studies include:

A. **High speed aerodynamics and large transport category aircraft.**

1. Most effective configuration for the airframe - Technology Concept Aircraft
   - Baseline configuration-canards with cranked delta wing
2. Wind tunnel and CFD work - Mach 2.4 computational fluid dynamics modeling
   - Optimization techniques
   - Comparisons to wind tunnel testing
3. Airframe design –
   a. OEW (operating empty weight) reduction
   - Structural loading driven by thermo-mechanical and manufacturing processes
   - 60K hour durability at 350° F skin friction
   - Damage tolerance

   b. High lift devices
   c. External visibility system
   - Elimination of droop nose for visibility

B. **Propulsion Technology and Exhaust Gas Studies**

1. Engine technologies for sustained M>2 flight
   a. Mixed compression inlets for high performance
   b. Thrust cycles
   c. Stage 3 noise reduction drives the exhaust sizing
   d. Low nitric oxide (referred to as NO_x) emissions
   e. 3000 percent increase in operating time at max power
2. Studies and compromises to incorporate environmental issues
   a. Nozzle size linked to noise reduction
   - High mass flows in subsonic flight
   - Long inlet design

   b. Composite materials required
   - 3500 degree F/ 9000 hour engines

C. **Environmental Impact Studies**

1. Sonic Boom Attenuation - Studies of airframe shape to reduce intensity of shock
2. Nitric Oxide and Nitrous Oxide Reduction
3. Noise level reductions

D. **Market and Business Impacts**
1. Cost of operations
2. Appeal to large carriers

These issues were examined in the years 1990 to 1998. Wind tunnel tests were run; computational fluid dynamics computer models were extensively developed, engine inlet and exhaust designs were developed, and a host of other aircraft related work was performed. The environmental side of the studies included high altitude research of jet engine exhausts and a rather extensive study on how to attenuate the sonic boom. The question on how the aircraft would meet the Stage III noise requirements that were in effect was singularly daunting. How could the design insure that the decibel level of the engines exhaust was below the sound of highway traffic? Noise reduction was to be a major factor in the engine exhaust and nozzle design. Favorable progress was made on all of these issues.

PROGRESS

A. HIGH SPEED AERODYNAMICS AND LARGE TRANSPORT CATEGORY AIRCRAFT.

Structure

Perhaps the easiest of the technical challenges was to design a baseline airframe to meet the performance requirements expected from the proposed supersonic transport category aircraft. The early decision to use a cranked delta wing with engines mounted in pods appears to be the logical derivative from the original SST work of the 1960s. It was determined that the United States version of this aircraft would not have a droop down nose for visibility during landing and takeoff. Therefore the avionics requirements for remote visual aids and special displays were assumed from the start.

Two of the challenges were thermomechanical loading and the necessity to reduce the structural weight to accommodate larger payloads. The first of these, thermomechanical loading, is a term that had come into the engineering lexicon with the advent of high Mach number flight. The combination of the structural strength requirements and the durability requirements for an aircraft to encounter 350°F temperatures for long periods of time were difficult. The solution was to use composite materials specifically built for this purpose. Carbon fibers in a polyimide resin were selected for the major portions of the structure, and at the time the program was cancelled the analytical portion of the testing was not finished and the necessary hardware testing was yet to be accomplished. NASA had developed a polyimide-carbon fiber matrix composite that was considered to be the answer to this design challenge. The airframe would be largely composed of this material (Whitehead; 1999).

Configuration

The various configuration changes were set about a baseline Technology Concept Airplane (TCA). There were various "versions" of this design; principally the differences were how much sweep was given to the outer wing of the cranked delta and what high lift devices were used. In these wind tunnel and CFD tests, the wing area, span, aspect ratio, outboard sweep and horizontal tail area were changed. Part of the configuration changes included a canard. The final configurations, tested by the end of 1998, pointed to a lower swept outer wing with canards. The drag count at certain coefficients of lift was less, the trim drag was reduced, and the use of a variable camber leading edge flap all resulted in good possibilities for the configuration (Elzey, et.al; 1999). The difficulty with this configuration was that it was not conducive to producing a low-pressure sonic boom. The design key to reducing the sonic boom impact requires a low profile very swept aircraft. "Low-sonic boom design features include an arrow wing for long lifting length, long forebody, staggered nacelles, lifting arrow wing horizontal tail, and a smooth overall area distributions." (Boeing; 1989) Relief from the low sonic boom constraint was driven by the inability to predict whether such design efforts could achieve the low sonic boom goals. Studies finished to that point indicated "Even the low-boom configuration would highly annoy over 25 percent of the population." (Whitehead; 1999). The requirement to fly supersonic over populated areas was dropped and this decision relieved those aerodynamic design constraints. By the end of the program an efficient aerodynamic design to sustain Mach 2.4 had been worked out.

Propulsion

Early in the program, four challenges associated with the propulsion system were somewhat unique to a supersonic transport. These included:
(1) mixed compression inlets that had high safety margins;
(2) high specific thrust that achieve efficient supersonic cruise;
(3) very low nitric oxide emissions;
(4) significant improvement in operating times at max temperatures and pressures (Whitehead; 1999).

The constraints of the second and third of these propulsion challenges were most difficult. First, to achieve the required thrust without exceeding the noise requirements implied a careful sizing of the nozzle. Second was the requirement to reduce the NO_x production to a level designated as an equivalent of grams of nitric oxide production per kilogram of fuel less than five. This ratio of nitric oxide to weight of fuel is 5×10^{-3}. (EPA: 2001) The Concorde SST was used as a sample emitter and the target for the HSCT was considerably less than that sample. The Concorde index for NO_x was 20 compared to the HSCT target of 5. Comparisons to the Concorde performance in these latter two areas show how much work was going to have to be accomplished in the design of the engine to meet these tight constraints. At the time there was no equivalent military fanjet engine capable of meeting all the design requirements placed upon the HSCT.

Inlets

By establishing a baseline configuration early on, the engine designers could address these challenges in order. Research that was conducted identified that a two-dimensional bifurcated inlet would be the baseline. This inlet was essentially a two-dimensional split inlet duct leading into the engine fan section (Plencer, et.al.; 1998). The downside of using such a design was the increase in drag and weight, but in all other respects this 2-D inlet had advantages over the "translating or variable diameter" center body-inlet plug design.

Nozzle

The choice of a nozzle baseline was more difficult as the noise reduction criteria determined the size and configuration. The need to sustain supersonic flight and operate efficiently at low subsonic speeds dictated a long nozzle and hence a long engine. The outcome of the studies accomplished under the management of Glenn Research Center resulted in a two-dimensional mixer-ejector nozzle.

Core engine

The severe operating condition for this engine dictated a high operating temperature for a long time requiring ceramic matrix components for the combustion section. Development of these composite components was well under way when the program was cancelled. Compounding the design problem was the requirement for active cooling air within the combustion chambers, and this mixing changes the chemistry that is important for low nitric oxide emissions.

The turbine components would have to be of a composite material. One material that was being developed consisted of an oxidation resistant nickel-based super-alloy but this material was not, at the end of the program, selected as the definite choice (Mecure, 2000).

Nacelles and engine mounting

The Technology Concept Aircraft (TCA) configuration selected placed the four engines in individual pods mounted beneath the wings.

B. ENVIRONMENTAL

The two attempts to develop a supersonic transport aircraft in the United States were plagued by an unprecedented demand that the aircraft be environmentally safe. The political sensitivities of the environmental issues could not be ignored and the greatest challenge to the designers meeting the very specific environmental requirements. There was some debate about the validity of these requirements in protecting the atmosphere, but the propaganda effects of not attending to them in the design the HSCT would have, in all likelihood, stopped the program. As it turned out, the politics hung on the cost of such a development and less on the program's technical factors.

There were four areas of concern for the HSCT: airport community noise, stratospheric ozone depletion, sonic boom impact, crew/passenger radiation exposure.

The technical design challenges to meet specific requirements for each of these was mentioned earlier in this document, with the exception of the crew/passenger radiation exposure concern. The studies accomplished under the HSR program, in concert with European and Japanese air-carrier industry representatives, produced documents and data indicating the problem of high altitude radiation exposure as a legitimate concern. The High Speed Research program addressed the particulars of atmospheric ionizing radiation (AIR) in an attempt to determine the threat to aircrews and passengers. The primary concern was with high-energy neutrons at altitudes above 50,000 feet. Samples taken by NASA ER-2 aircraft[2] in 1997 were to be analyzed by the Department of Energy. The current view is that crews of all commercial air transports are classified as radiation workers by the EPA, the FAA, and the International Commission on Radiological Protection (Whitehead, et.al.; 1999). In effect, this means that all aircrews should be monitored for their exposure to high altitude radiation. However, as of the end of 2000 there were no international regulations that applied to aircrew exposure. This is a problem that has to be addressed in future years. Without further study, there are neither guidelines nor requirements placed upon designers to provide "radiation proof" cockpits and cabins. Currently the only guide available is one that applies to ground-based workers exposed to radiation. At the latitudes the HSCT was expected to operate, there would be restrictions on flight hour exposure time.

The Ozone Factor

A 1995 preliminary report for NASA indicated a concern for the amount of NO_x that would be released at the altitudes near the location where the ozone layer is formed. The study of the ozone layer and the effects of hydrocarbon emissions on the breakdown of this layer have been on going for several decades. NASA had a primary role in the upper atmospheric sampling that determined the extent of this breakdown. In the winter of 1988/89 indications of a major depletion of ozone over the upper latitudes of the Atlantic was discovered by NASA scientists flying airborne research aircraft out of Ames Research Center. As more information was gathered over the next several years, the conclusions about that region of ozone depletion were not conclusive enough to alter the belief that the HCST would not further damage the upper atmosphere. In any case, the goal for the HSCT was to have emissions well below that of the current air traffic that crisscrosses the Atlantic. It would mean programmatic suicide for any high altitude aircraft design team not to attempt to reduce the emissions of nitric oxide.

[2] The ER-2 is a modified USAF U-2R aircraft that was flown out of Moffett Field, CA and now Edwards, CA. It was ideally suited to study the AIR at the altitudes required.

The impact on the ozone layer remains to be fully understood after decades of jet aircraft flying between 25,000 and 40,000 feet across the same airway systems in the northern hemisphere. NASA commissioned a report from the Environmental Protection Agency to address the projected "modeling" of ozone depletion predicted from a fleet of 1000 to 1500 HSCTs in the mid-21st Century (EPA, 2001). This report relied heavily on the work an earlier study by NASA (Kawa, et.al. 1999). The Kawa work reported primarily on modeling of ozone, depletion and estimates of the impact of the chemistry changes that a fleet of HSCTs might contribute to in the upper atmosphere. Based on the lack of real data the report leaves doubt. The conclusion stated that an increase in skin cancer would probably occur over a period of time due to supersonic transports, and the incidence of melanoma and skin cancer mortality would be significantly greater than had there been no HSCT fleet. These reports taken as a whole have created an impediment to political support for the HSCT.

The Sonic Boom

The attempt to eliminate the annoyance of the sonic boom over populated areas was unsuccessful for several reasons. The results are summed up in the statement: "The design effort did result in significantly reduced sonic boom pressure levels on the earth's surface, but there was also a reduction in aerodynamic performance" (Whitehead; 1999). Technically this had to do with preventing what was termed the N wave from forming. The N wave is the shape of the pressure pattern that results as all of the shock waves forming on surfaces of the aircraft coalesce into a region of one high pressure wave. NASA flight test studies showed how the N wave is formed. Subsequently, researchers applied various aerodynamic shapes to reduce the amplitude of the wave. Using the existing and predicted data, studies were begun to determine the acceptability of the reduced sonic boom wave. These studies were more on the nature of surveys of public opinion. Their results were not scientifically conclusive, but the indication was that a significant proportion of the population affected would be "highly annoyed".

It might bear pointing out that a large number of people who live in homes or apartments near major airports are also highly annoyed. One might make the observation that restricted routes for supersonic flight over the continental United States would result in better statistical analysis. The final plan was not to fly supersonic over the inland of the United States.

One further note about the acceptability of the sonic boom can be made. The question arose as to the affect of the boom on sea life. Since all of the supersonic flights would be made over the oceans they might be harmful to sea animals. Because the over pressure levels of a sonic boom may reach 12 pounds per square inch there could be reason for concern. However, the attenuation of the shock wave through water is such that at depths of 15 or more feet it is negligible. On shallow coastal waters the results of the study indicated that the sonic boom would have no affect on sea mammals (Darden; 1998).

The methodology for determining this response was from a study of gray seals that were exposed to three sonic booms per day. There was another study to be undertaken in 1998 that would look at the behavior of harbor seals. Such studies indicate the extent of even this environmental concern upon design constraints.

WHAT MAY REMAIN TO BE ACCOMPLISHED

The work on solving the issues associated with these design challenges would have continued had not the HSR program been cancelled. In the synopsis given above, several areas can be identified that might have been contributory to private industry had they been funded to completion. The most important of these with respect to future high-speed research can be tentatively identified.

A. Continued development of a polyimide-carbon fiber matrix for use as structure in large transport category aircraft.

B. Continued research on sonic boom abatement.

C. Build and test full-scale supersonic cruise engine with low noise and NO_x emissions.

D. Continue with detailed studies and experimentation (using military aircraft) in the area of noise around large airports.

E. Continue search for direct evidence that jet engine exhaust emissions have an affect upon the ozone layer.

F. Develop aircraft structure (skin, windows, etc.) to protect crew and passengers from harmful radiation.

G. Make final determination of permissible exposure rates to AIR.

H. Prototype a scaled down HSCT or RPV version for demonstration of flight and handling qualities.

I. Revisit the health impacts studies once a better understanding of the effect of engine exhaust upon the ozone is known.

CONCLUSION

At the present time, the U.S. aerospace industry is in the doldrums. The airline industry is suffering with bankruptcies and deficits. There are only a few major aircraft manufacturing companies still producing aircraft. The competition from Europe's aerospace industry is intense. Boeing Corporation has recognized the advantages of higher speeds for today's commercial transport category aircraft and has elected to produce a high transonic speed airliner that is a departure from the standard configuration of the transport jet aircraft that have been built since the rollout of the Boeing 707 about 45 years ago. The shutdown of the

HSR effectively stopped investment by industry into high speed flight for public transportation. What is more pernicious is that the ending of the research program halted the work being accomplished on several important technical challenges, any of which could revitalize certain parts of the industry.

Apart from the High Speed Civil Transport NASA was conducting other studies and development work under HSR. One program was called Hyper-X and was later Christened the X-43. NASA management had hoped to develop a hypersonic, Mach 7-10 test vehicle that would utilize scramjet technology in the first decade of the 21st century. This program had an ignominious start after a five-year design and manufacturing process. The first flight test ended in failure when the Pegasus rocket carrying the test vehicle lost one of its control fins and was destroyed (Smith: 2001). The first successful flight test did not occur until the spring of 2004 and funding for advanced versions of the X-43 is in question. (Shelleck: 2004)

Yet the heart of the program was the HSCT and the void in its development keeps the US aerospace industry tethered to a very old technology and aircraft design. The ending of the HSR program left several research teams working with no clear purpose. Expectations for the research were affected. Had NASA continued funding of the work on the HSCT it seems possible the aerospace industry and the flying public would have benefited. The list of possible outcomes of continued research on the HSCT serves to illustrate what might have been.

1. There was risk involved in continuing the program but that risk was only financial. Given the capabilities of aerospace today, it is clear that the work being accomplished during the ten years the HSCT was funded would have produced an aircraft capable of demonstrating a design success over the challenges that existed when the United States ended the SST program 30 years ago. The systematic approach taking place on the HSCT had already succeeded in designing the Technology Concept Aircraft that offered promise. This TCA, or a derivative of it, was capable of meeting the operational requirements over intercontinental high-speed air travel.

2. The airframe structural development, had it continued, would be a significant step in developing materials and manufacturing techniques applicable to any supersonic large category aircraft. Since the introduction into composite materials use in the 1960s and 1970s an entire new industry has matured; and where once composite aircraft parts were difficult to manufacture and maintain, today such processes are routine.

3. The work that was accomplished on the propulsion system for this aircraft was perhaps further along than any other part of the development. Today large engines producing very high thrust to weight ratios are available. Of all the aspects of the HSCT, the engine development would have had a significant positive impact on the commercial aviation industry. Overcoming the noise and emissions problems would have allowed airframe designers more options in building new transport category aircraft.

4. Today the fully automated, fly-by-wire, glass cockpit, transport category aircraft is operational. Application of this technology to the HSCT would have ushered in the era of fully automated flight operations. Such aircraft, either subsonic or supersonic, will in the future not require man-rated skills in order to operate. This would have been a necessity in the HSCT, but one that is already projected for the future of the air carrier business. The HSCT design would have advanced full automation (autonomous flight) that today is being applied to all types of aircraft from both manned and unmanned.

5. A few prototype HSCTs would have given the aerospace industry the opportunity to pick up where it left off in the design of high performance commercial aircraft. In the 1990s, NASA attempted to create a Reusable Launch Vehicle (RLV) or single stage to orbit space plane. The technical issues were more difficult than had been anticipated, and the program ended after a lack of progress. In the past year the idea was resurrected under the President's space initiative. It has been argued by flight test and aero researchers that had we continued the steady pace of high speed transport development from the 1970s to the present, many of the technical problems would already have been addressed; and at the least the United States would have built and flown large high speed aircraft that could be used as test beds for further development of an RLV. The SR-71 and the X-15 were at the leading edge of that work 30 years ago. Today we do not have such test aircraft available.

The US aerospace industry has been through this pattern before. Had the last two Presidential Administrations seen fit to at least continue with the projects already in progress under the HSR, the gap between what was learned and what we might have achieved would not be as great as it is now. The burden of continuing research was more than any single company was willing to bear. The political factor was more devastating. NASA failed to convince the Office of Management and Budget in 1997 that the HSCT was worth pursuing from a technological as well as economic basis. The response from the single major airframe manufacturer, Boeing, was equally damaging to the hopes of continuing the HSCT development. NASA's Administrator at the time, Dan Goldin, was unable to convince industry to continue funding the necessary work.

Each of the developmental projects listed should have been continued with federal support. What could we learn about carbon-polyimide composites as structural material? Was the combustion chamber design for the engine capable of meeting the sustained high temperatures that were required? Would the actual ratio of NO_x to fuel burned be acceptable? Is there a significant cause and effect relationship between jet engine exhaust and ozone depletion? Would supersonic flight at 50,000 feet cause the sonic boom to be a real problem or would it have been no worse than the sound of a subsonic jet flying at 30,000 feet over populated areas? Can we produce large thrust engines that meet stage III requirements?

This paper does not mention the potential economic variables associated with the HSCT; they may be the only monumental task remaining. The work done to meet the technical requirements for a supersonic transport seems to show progress in all directions. Had the funding continued it could have been proven that there were no technical problems which would have prevented the introduction of such an aircraft into operations. Only the costs of development and initial operation would have been the deciding factor. One day we will ask why we didn't find out.✈

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