PROGRESS TOWARD MEETING THE PROPULSION TECHNOLOGY CHALLENGES FOR A 21ST CENTURY HIGH-SPEED CIVIL TRANSPORT

Robert J. Shaw
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Leigh Koops
General Electric Aircraft Engines
Evandale, Ohio 45249

Richard Hines
Pratt & Whitney Aircraft
Hartford, Connecticut 06108

Introduction

Ongoing NASA-funded (ref. 1, 2) and privately funded studies continue to indicate that an opportunity exists for a second generation supersonic commercial airliner, or High-Speed Civil Transport (HSCT), to become a key part of the 21st century international air transportation system. Long distance air travel is projected to increase at about 5 percent per annum over the next two decades (ref. 3-5). This projection suggests that by the year 2015, more than 600,000 passengers per day will be traveling long distances, predominantly over water. These routes would be among the most desirable for an HSCT as part of the international air transportation system. Beyond the year 2000, this portion of the air transportation market is projected to be the fastest growing segment.

The potential market for an HSCT is currently projected to be anywhere from 500-1500 aircraft over the 2005-2030 time period. Such an aircraft fleet size would represent a considerable share of the potential large aircraft market. However, the projected HSCT fleet size is very sensitive to a number of factors including the level of available technology. The technologies employed in any commercial aircraft design must improve product performance but not at the expense of significantly increased costs (acquisition, operation, and maintenance).

Simply stated, the HSCT will be a technology driven airplane. Without significant advances in airframe and propulsion technologies over the levels currently available, there will be no second generation supersonic airliner! In order for the HSCT to become a reality, the technologies developed must contribute to an aircraft design which is (1) environmentally compatible and (2) economically viable. This paper will briefly describe the propulsion technology challenges which must be met prior to any product launch decision being made by industry and the progress toward meeting these challenges through NASA's High-Speed Research (HSR) Program, a partnership between NASA and Boeing, McDonnell-Douglas, General Electric, and Pratt & Whitney.

Environmental Challenges

The two environmental challenges which must be met before an HSCT product launch could be considered are atmospheric ozone depletion and airport noise. Meeting these challenges requires advances in propulsion technologies, specifically ultra-low NO_x combustor technology to meet the ozone depletion challenge and low noise propulsion system technology to address the airport noise challenge.

Ozone Depletion

Potential depletion of the Earth's protective ozone layer is attributed to HSCT engine exhaust products, specifically the nitric oxide (NO_x) levels. Thus combustor designs must evolve that produce ultra-low levels of NO_x such that no harm is done to the ozone layer while at the same time having high levels of combustion efficiency and operability across the mission profile.

Airport Noise

The other HSCT environmental barrier challenge which must be met is aircraft noise during takeoff and landing conditions. The prime contributor to an HSCT noise signature is the jet exhaust , and thus an approach to quieting the jet exhaust without seriously impacting propulsion system performance or weight must be developed. Any HSCT propulsion noise reduction approach pursued must take into consideration that a stricter noise rule than the current FAA FAR 36 Stage 3 may be in place by the time an HSCT would enter the fleet, and thus candidate approaches must be evaluated for potential to have even greater noise reduction than those currently required for certification of subsonic aircraft.

The solution to the HSCT noise challenge will require a systems engineering approach. Contributions to the vehicle noise reduction will come from several sources: advanced exhaust nozzles, engine cycle characteristics, advanced high-lift concepts, and possibly advanced aircraft operational procedures such as programmed lapse rate.

Economic Challenges

In order for the HSCT to become a reality, it must be a profitable venture, both for the aircraft and engine manufacturers as well as for the airlines. The already mentioned studies being conducted have in some cases involved surveys with the flying public. These surveys suggest that for the long haul, primarily over water routes across the Atlantic and Pacific Oceans, travellers would be willing to pay as much as 20 to 30 percent more for tickets with the prospect of halving the travel time. The motivation to pay more for reduced travel time not too surprisingly increases as the travel time exceeds 4-5 hours. This information gives one some insight into what economic viability means for an HSCT in the view of the travelling public, the ultimate customer.

System Requirements and Technology Drivers

Figure 1 compares the Concorde, the world's only operational commercial supersonic aircraft, with the current perspectives on the HSCT. While the Concorde remains an engineering marvel almost 30 years after its maiden flight, it achieved neither environmental compatibility nor economic viability. Hence only 16 Concorde aircraft were ever built and 13 are currently in operation, serving selected trans Atlantic routes with fares several times higher than widebody subsonic aircraft. For the HSCT to become a reality, it is envisioned the aircraft design must have at least the features depicted on this figure.

Translating these system level requirements shown on figure 1 into those for the HSCT propulsion system suggests that the engine manufacturers must design, build, and certify an HSCT propulsion system that:

—has performance levels comparable to a supersonic military fighter engine.

—has durability and life characteristics that are comparable with subsonic commercial propulsion systems.

—contributes to meeting the HSCT environmental challenges of NO_x and community noise.

—contributes to meeting HSCT economic viability requirements.

Clearly these are some tremendous challenges facing the HSCT engine designers and currently available propulsion technologies are not adequate. Figure 2 gives a more detailed view on the technology challenges related to the HSCT propulsion system in terms of emissions, noise, and durability. The HSCT propulsion system will be big, as figure 3 depicts. The overall length will be about 50 feet with a maximum diameter of about 50 inches. This overall system size will provide a significant design challenge for all components of the propulsion system. As an example, figure 4 shows that the high pressure turbine disk for the HSCT is estimated to be about twice the size of the disks found in current subsonic transports.

Technology Challenges and Accomplishments

Thus the technology challenges related to environmental compatibility and economic viability for the HSCT propulsion system and indeed for the whole vehicle are significant. In order to address these technology challenges, both for the airframe and the propulsion system, NASA began the HSR Program in FY 1990 as indicated in figure 5. Since its inception, the HSR Program has had as a vision the development and transfer of the high risk, high payoff technologies to the industry which in turn would then be able to make a lower risk product launch decision at the time when all the factors contributing to a commercial aircraft launch are considered. The HSR Program was constructed to so as to first address the environmental challenges (Phase I) and only if there were viable solutions developed for NO_x and noise reduction would the Phase II Program be initiated. The Phase II Program would have as its emphasis the development of the highest payoff technologies associated with economic viability.

To date, the HSR Program has enjoyed considerable technical success. Viable laboratory solutions for the environmental challenges were developed and demonstrated. Progress on the Phase II efforts has also been great. The propulsion technologies for the critical components, including the advanced high temperature engine materials being developed, are being successfully transitioned from the laboratory to the larger scale component designs incorporating the advanced materials systems under development. These components will be tested and evaluated in the more realistic and severe engine environment. Figure 6 overviews the propulsion element content of the Phase I and II efforts of the HSR Program.

Progress has also been significant in the airframe element of the HSR Program. Specifically, advanced high lift approaches have been developed and demonstrated in model scale along with improved supersonic performance planform configurations as well as advanced composite materials for the airframe structure which are capable of withstanding up to 350 °F temperatures which the HSCT will encounter. In addition concepts for advanced flight deck designs have been evolved utilizing synthetic vision which offer possibilities for increased levels of aircraft safety beyond those available today.

The remainder of this paper will briefly overview some of the technology advancements being made by the propulsion element of the HSR Program.

Technology Concept Propulsion System

Since the HSR Program is a focused technology program driven by vehicle requirements (including the propulsion system), it is necessary to have a technology concept aircraft to focus the technology development efforts so as to make informed decisions about which technologies to pursue and which can be discarded, either being too risky to pursue or having too little payoff to merit the investment of critical resources. In 1996, a technology concept aircraft was developed by the NASA/industry team along with a technology concept propulsion system as depicted in figure 7. This "paper propulsion system" was configured after incorporating the results of over 12,000 hours of scale combustor, nozzle, and inlet tests, over 50,000 hours of engine materials testing, and over 250 work years of propulsion and airframe systems studies. The technology concept propulsion system will continue to serve a critical role in the remaining years of the HSR program as it will enable NASA and industry personnel to evaluate individual component and subcomponent technologies against the overall system requirements.

Figure 8 lists some of the major technology advances made for the various components of the HSCT propulsion system. These will be briefly reviewed in the following paragraphs.

Inlet

A series of subscale (approximately 25 % HSCT scale) supersonic wind tunnel tests have been conducted of candidate axisymmetric and two dimensional mixed compression configurations. All tests were conducted in the NASA LeRC 10x10 Supersonic Wind Tunnel to evaluate supersonic performance and isolated component operability. Figure 9 show one of the two dimensional inlet configurations tests conducted in the 10x10SWT. To date all tests have been coldpipe tests, that is they did not involve engine testing. Future tests will involve using a GE J85 turbojet engine so as to examine inlet-engine operability requirements.

In addition, a large scale simulated inlet-engine operability test was conducted in Russia this past year as part of the US/Russia TU-144 program. Figures 10 and 11 show the overall setup and a close-up of the simulated supersonic inlet flowpath. The engine used for these experiments was an RD36-51A which was used on the original TU-144 aircraft. These test results are giving the NASA and industry personnel added insight into some of the important design features for the subsonic diffuser of the HSCT inlet and in particular how close coupled the inlet and fan can be without adversely affecting performance and operability. Reference 6 gives added information on these highly successful international tests efforts.

Combustor

A large number of flame tube (figure 12) and subscale sector (figure 13) tests of candidate ultralow NO_x combustor configurations have been tested in NASA and industry facilities since the HSR Program began in 1990. Tests have been conducted of both Lean Premixed-Prevaporized (LPP) and Rich Burn/Quick Quench/Lean Burn (RQL) configurations. Both flame tube and sector test results have been promising with NO_x results being measured in the EI range of 2-7 gm NO_x/kg fuel being measured. A combustor downselect will occur in 1998 and the most promising configuration will then be evaluated in both full size sector and full annular rig testing in the remaining years of the HSR Phase II Program.

The HSCT combustor cannot rely on conventional wall film cooling techniques if ultra low levels of NO_x are to be achieved. The HSR program has been developing a Ceramic Matrix Composite (CMC) material from which a combustor liner could be designed that would require only backside cooling. Initially a number of candidate fibers, matrices, and processing techniques were evaluated, but in 1996 a SiC based CMC was selected which incorporates a melt infiltration processing technique. As figure 14 shows, the HSR program has had great success in taking this material from the laboratory and fabricating complex three dimensional shapes more representative of a combustor liner. Durability tests are currently underway to evaluate material performance in the oxidizing and reducing environments of an HSCT combustor. Future plans call for fabricating and testing full size liners as part of the full size annular rig tests to be conducted.

Nozzle

Like the combustor, a large number of small scale (approximately 1/7 to 1/10 HSCT scale) nozzle configurations have been designed and tested to evaluate the most promising approaches for significant reductions in noise associated with the exhaust jet at both takeoff and landing conditions while at the same time maintaining high levels of aerodynamic performance (i.e. thrust coefficient) at low speed conditions. The HSCT nozzle design must be a balanced one which addresses both aerodynamic and acoustic requirements simultaneously. Many of the tests have been dedicated to acquiring fundamental data so that the underlying physics of the nozzle internal flowfield and especially the mixing region are well understood.

Figure 15 is an example of an early configuration tested in the Boeing Low Speed Aeroacoustics Facility (LSAF). The small scale test results have been most encouraging as sideline noise levels at takeoff conditions below 100 EPNDB have been measured which compares to a 120 EPNDB level measured for the Concorde. Based upon not only the many thousands of hours of test data but also the supporting airframe and propulsion system studies, the NASA/industry team selected the mixer-ejector nozzle as the approach which offered the greatest potential for the HSCT application. Successive generations of small scale tests are continuing to pursue mixer-ejector configurations which promise additional noise reduction and improved aerodynamic performance.

In addition to the isolated nozzle tests, the impact of the airframe on the mixer-ejector nozzle performance (aerodynamic and acoustic) has been evaluated through tests conducted in the NASA Ames National Full Scale Aerodynamic Complex (NFAC) as shown in figure 16. This 13.5 percent half plane model test results have given the US team confidence that the integration effects can be minimized.

Future plans call for the design, fabrication, and testing of a series of large scale models of the most promising configurations. These test will evaluate both aerodynamic and acoustic performance at low speed conditions for the approximately 60 percent models. This comprehensive large scale data base will provide insight of the effects on both aerodynamic and acoustic performance of scale as well as the realistic engine environment.

Advanced materials systems are critical to all aspects of the design of a viable HSCT nozzle system. Specifically the nozzle must have acceptable aero/acoustic performance, weight, and durability. A number of candidate materials systems have been evaluated through a variety of design, fabrication, test, and analysis activities. Based on this comprehensive data base and the airframe and propulsion system studies, materials downselects were recently completed as depicted in figure 17. Emphasis in the HSR Program is now turning to refining the fabrication/scale-up approaches selected for each of the nozzle subcomponents and evaluating in benchmark tests to be conducted at NASA Lewis. The final validation tests in the HSR Program will involve placing these subcomponents in the large scale nozzle models for evaluation in the hostile engine environment.

Turbomachinery Disk Materials

Two other material systems critical to the design of a viable HSCT propulsion system are those required for the turbomachinery disks as well as the turbine airfoils. The extended time at temperature requirements of the HSCT require that the disks for both compressor and turbine have a critical balance of tensile, fatigue, and creep strength as well as fatigue crack growth resistance. These requirements exceed the capabilities of any of the available Nickel based superalloys. The HSR Program has evaluated a large number of experimental alloys (figure 18) and identified promising candidates which have met the HSR goals as the figure suggests. Emphasis is now turning to taking these most promising alloys and evaluating the scale-up approaches for forging and heat treating that-maintain the critical performance characteristics. Appropriate spin pit tests will be conducted as the final technology validation efforts for the HSR Program.

Turbine Airfoil Systems

The materials system for the turbine airfoil system really consists of three components-single crystal Nickel based airfoil superalloy, bond coat, and thermal barrier coating. Significant progress has been made in the HSR Program to date on developing experimental alloys which are significantly better than those currently available for production applications (figure 19). Emphasis in the remaining years of the HSR Program will be to combine the three components into a turbine airfoil design and demonstrate technology readiness through appropriate rig tests.

Concluding Remarks

NASA's High-Speed Research Program has been formulated to provide the US industry with the critical technologies needed to support an informed decision by industry as to whether to launch an HSCT early in the next century. The financial risk to launching an HSCT without adequately mature and proven technologies in hand is enormous. Industry estimates indicate that it will cost at least $13-15 billion to design , build, and certify an HSCT once the decision to launch is made. While such amounts seem incredibly large, the financial returns estimated for a fleet of 500-1500 aircraft also must be considered. Industry estimates for such a fleet including the initial aircraft as well as spare parts and maintenance indicate $200 billion in sales may be realized. Thus it appears that the product launch of an HSCT will be a major decision for the commercial aerospace industry to make which will have financial implications which will be far reaching.

To date the HSR Program has provided industry with the high risk, high payoff airframe and propulsion technologies which suggest the vision of an HSCT becoming part of the 21st century international air transportation system is alive and growing. However, the maturity of these technologies, sometimes called the Technology Readiness Level (TRL) by NASA is still much too low for industry to consider the risk of a product launch decision as being acceptable. It is therefore critical that the HSR Program continue to successfully mature these technologies and transfer them to industry to contribute to reducing the risk of a product launch decision to acceptable levels.

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2. "Study of High-Speed Civil Transports," NASA CR–4235, 1989

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4. Current market Outlook-1994: World Market Demand and Airplane Supply Requirements. Boeing, Seattle, WA, 1994.

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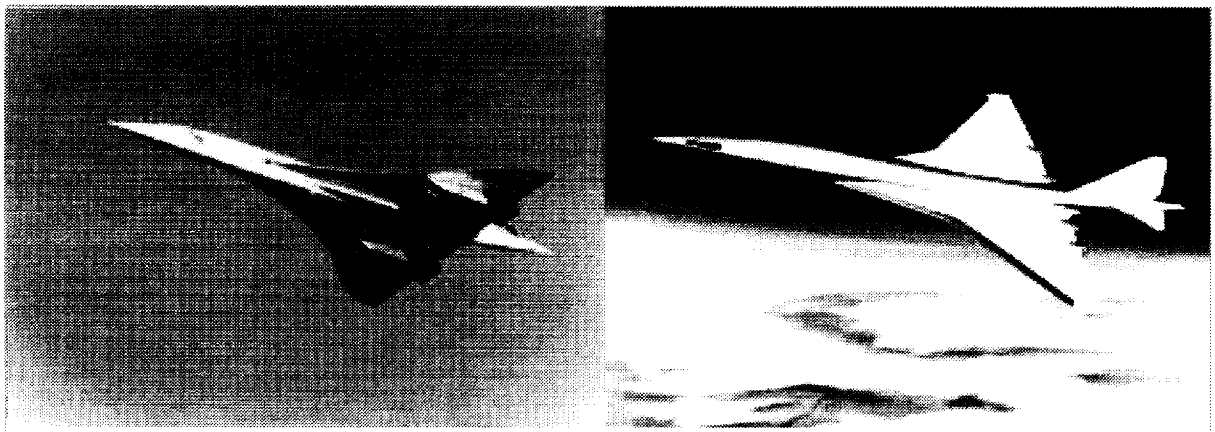
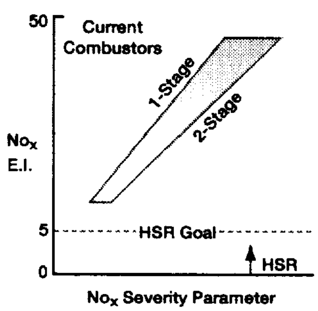


Concorde		HSCT
3000	Range (n.mi.)	5000-6500
128	Payload (passengers)	250-300
400,000	Weight (lb.)	750,000
Exempt	Community Noise Standard	FAR 36 Stage III - XdB
Premium	Fare Levels	Standard + ≤ 20% premium
20	Emissions Index	5

Figure 1 Comparison of Concorde to High Speed Civil Transport

EMISSIONS

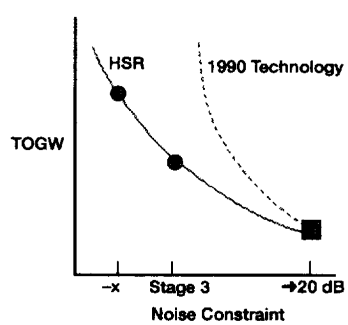
A Mach 2.4 HSCT will cruise at altitudes coincident with the highest concentration of atmospheric ozone. Unconventional combustors are required to reduce NO_x emissions to levels which have no significant impact on the Earth's ozone layer.



This challenge requires novel combustors and adv. materials.

NOISE

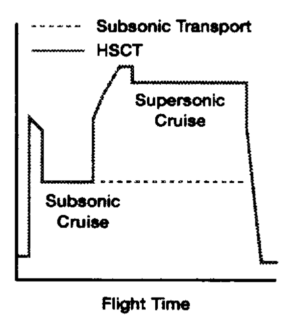
High specific thrust engines optimized for supersonic cruise have high jet velocities and are inherently noisy. Unconventional engines/nozzles are required to achieve compliance with FAR 36 Stage 3 noise regulations while providing acceptable subsonic and supersonic cruise performance.



This challenge controls inlet engine nozzle selection.

DURABILITY

Over their entire life, current tactical fighter and subsonic commercial transport engines accumulate 250–300 hours at max cycle temperatures and stress levels. HSCT propulsion systems must operate at these conditions for 9,000 hours. Thus, the HSCT duty cycle is 30X that of current engines.



This challenge demands advanced high-temp materials and cooling schemes.

Figure 2 HSCT Propulsion System Technical Challenges

HSCT Propulsion Systems Are Big Engines

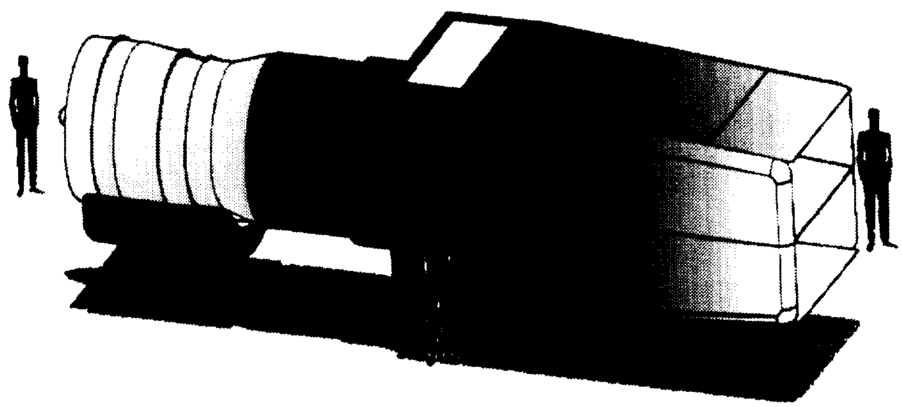


Figure 3 Artist's concept of the full scale HSCT propulsion system

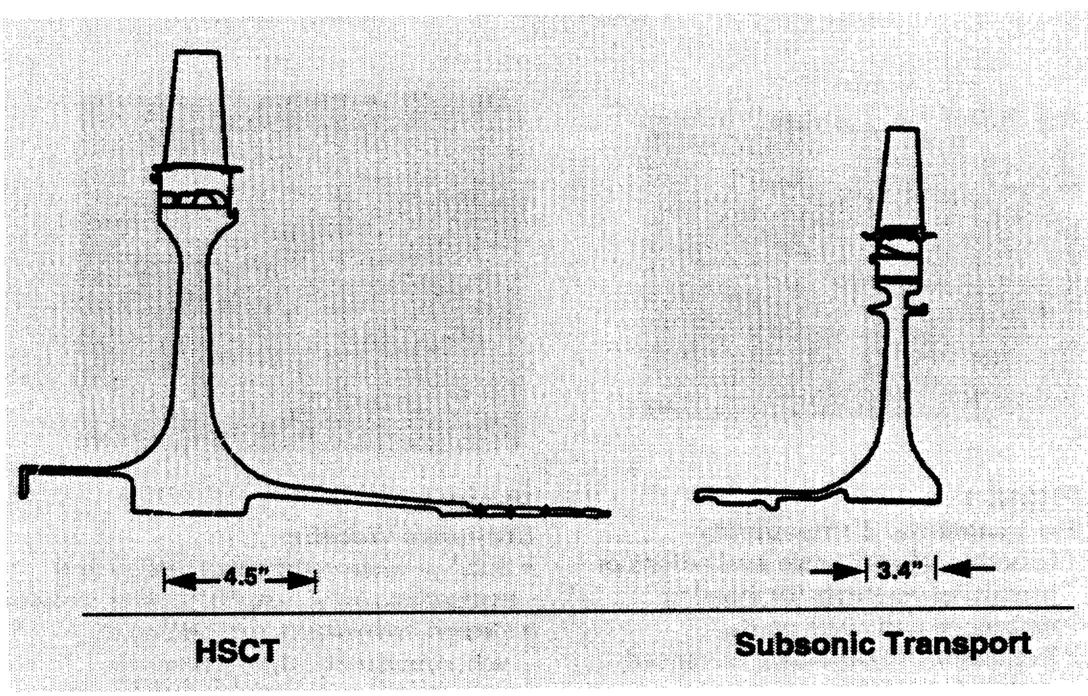


Figure 4 Comparison of High Pressure Turbine Disk Sizes for HSCT and Subsonic Transport Propulsion Systems

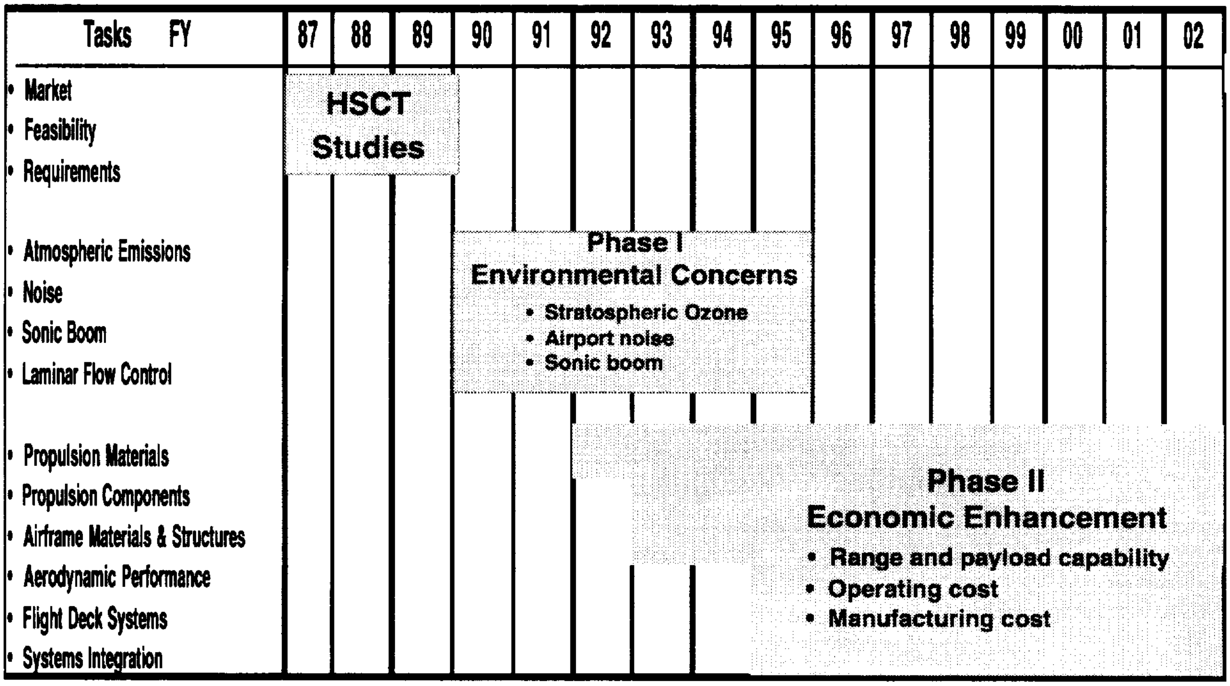
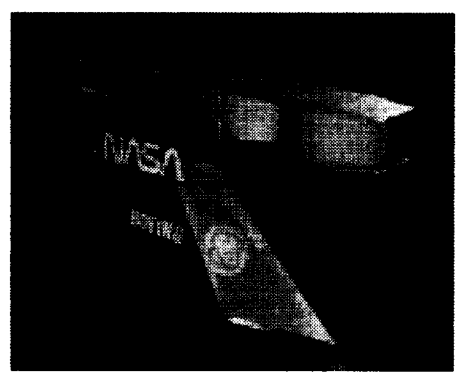


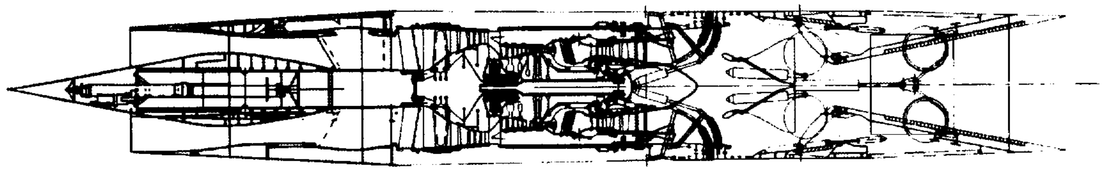
Figure 5 NASA/Industry High-Speed Research Program



PHASE 1
Environmental Compatibility
- Laboratory/small scale evaluations of promising concepts for meeting emissions and noise goals
- Evaluations of candidate advanced materials systems
- Propulsion system evaluations of candidate cycles

PHASE II
Economic Viability
- Sub/full scale component design and evaluations (inlet, fan, combustor, nozzle)
- Design, fabrication, and testing of subcomponents using advanced materials (eg. combustor liners)
- Refinement of downselected cycle to meet mission requirements

Figure 6 High-Speed Research Program (Propusion Element)

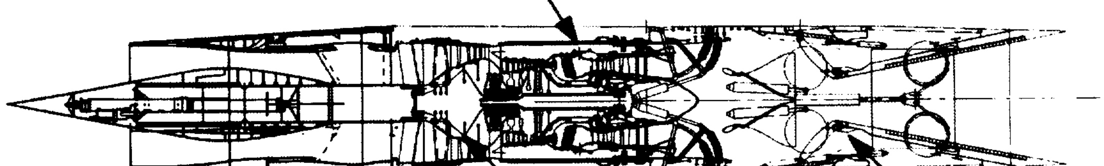


HSR Technology Concept Propulsion System

- Two dimensional inlet
- Mixed flow turbofan cycle
- Two dimensional mixer-ejector nozzle

Figure 7 HSR Technology Concept Propulsion System

- Completed initial subscale flame tube and sector tests for a variety of Lean Pre-mixed, Pre-Vaperized (LPP) and Rich Burn, Quick Quench, Lean Burn (RQL) concepts and demonstrated ultra low NO_x potential of both approaches.
- Developed a CMC material which shows great promise for use as HSCT combustor liner which meets environmental and economic requirements.



- Completed subscale tests of candiate axisymmetric and two dimensional concepts.
- Completed large scale inlet/engine oberability tests as part of US/Russia TU 144 program.

- Developed experimental alloys for turbomachinery disk and turbine airfoil applications which show promise of meeting HSCT design requirements.

- Completed initial small scale nozzle tests of configurations which meet aerodynamic and acoustic performance goals.Have identified approaches for further performance improvements.
- Completed evaluation of candidate materials systems for nozzle and demonstrated fabrication scale up capabilities.

Figure 8 HSR (Propulsion) Major Technology Advancements

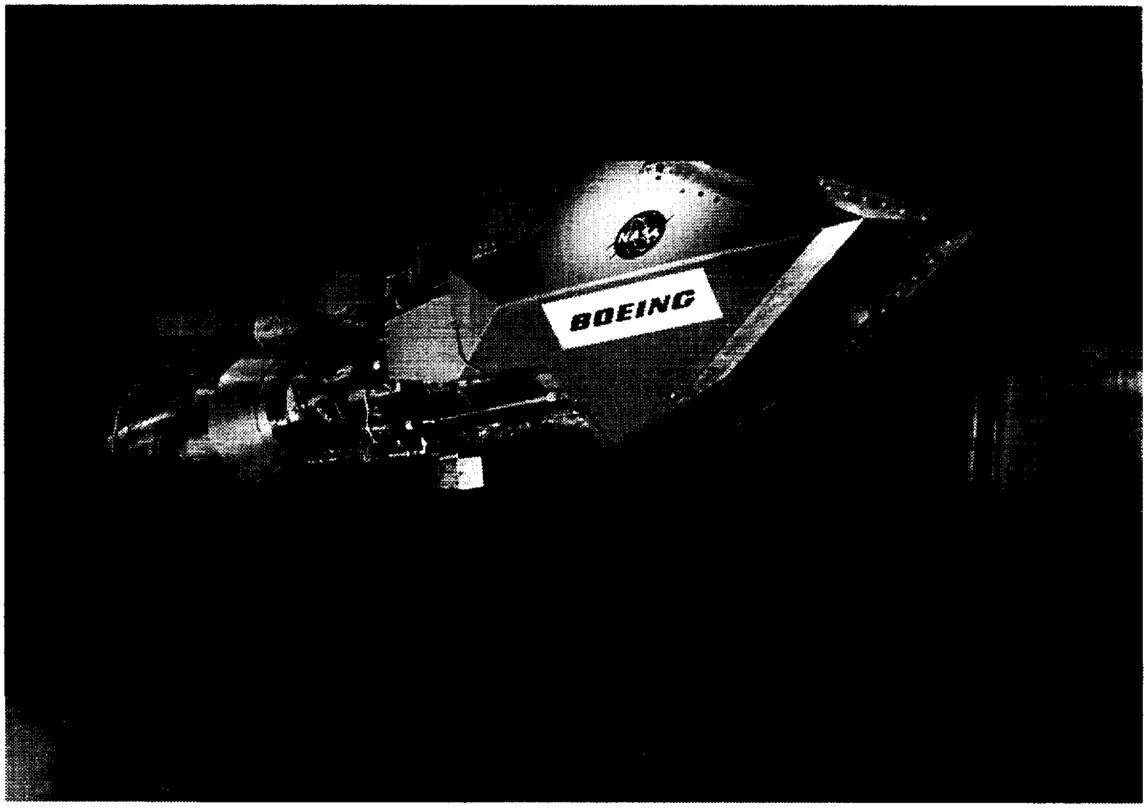


Figure 9 Two Dimensional Inlet Test in NASA LeRC 10x10 Supersonic Wind Tunnel

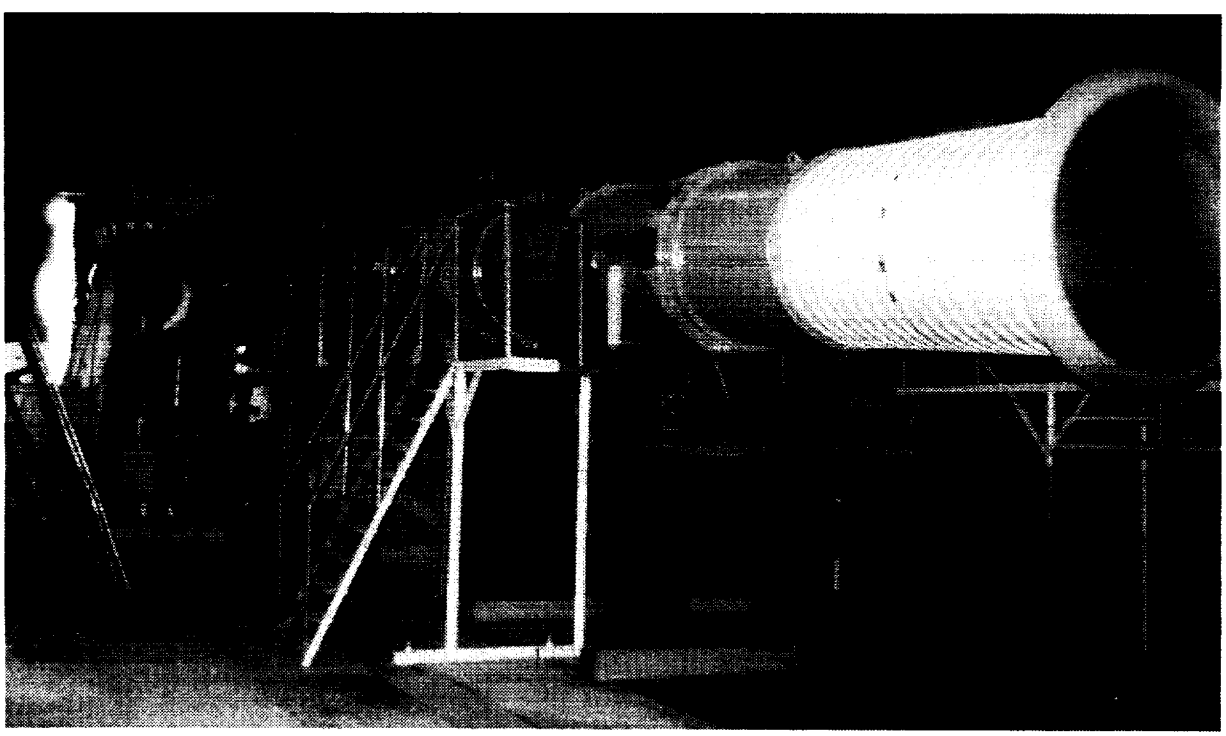


Figure 10 US/Russia TU 144 Engine Ground Test Setup

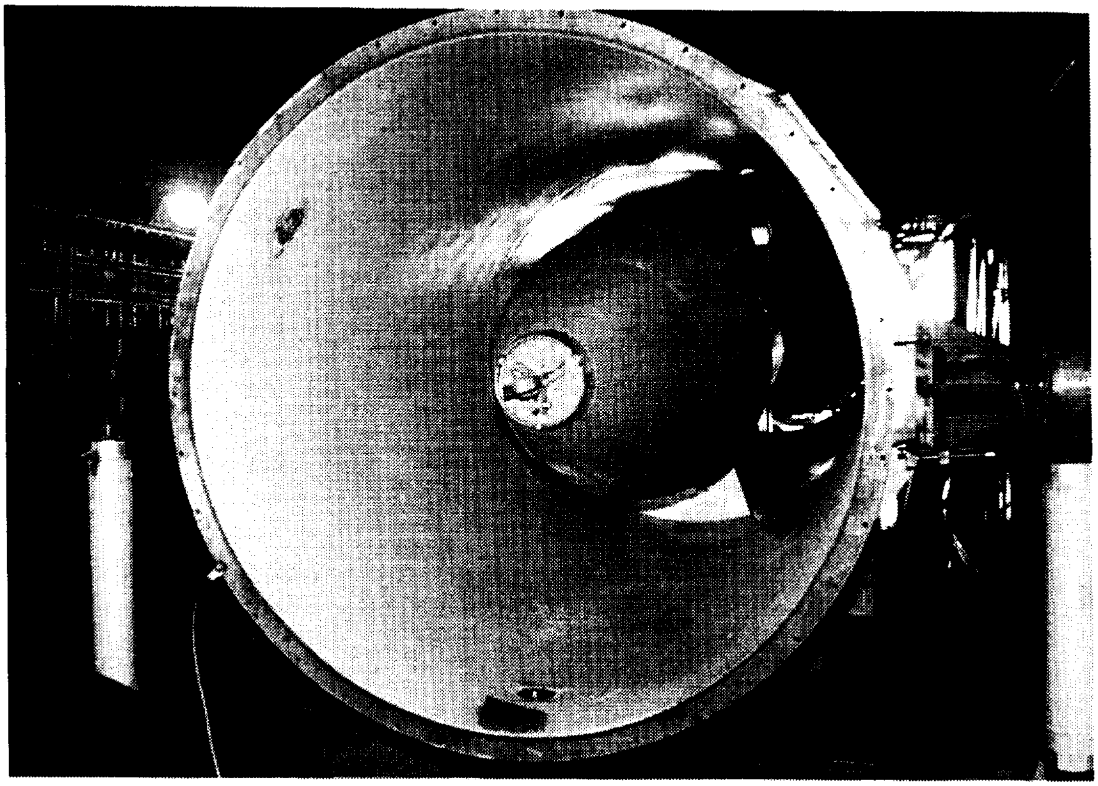


Figure 11 Closeup View of Simulated Supersonic Inlet Flowpath

Flame Tube Tests

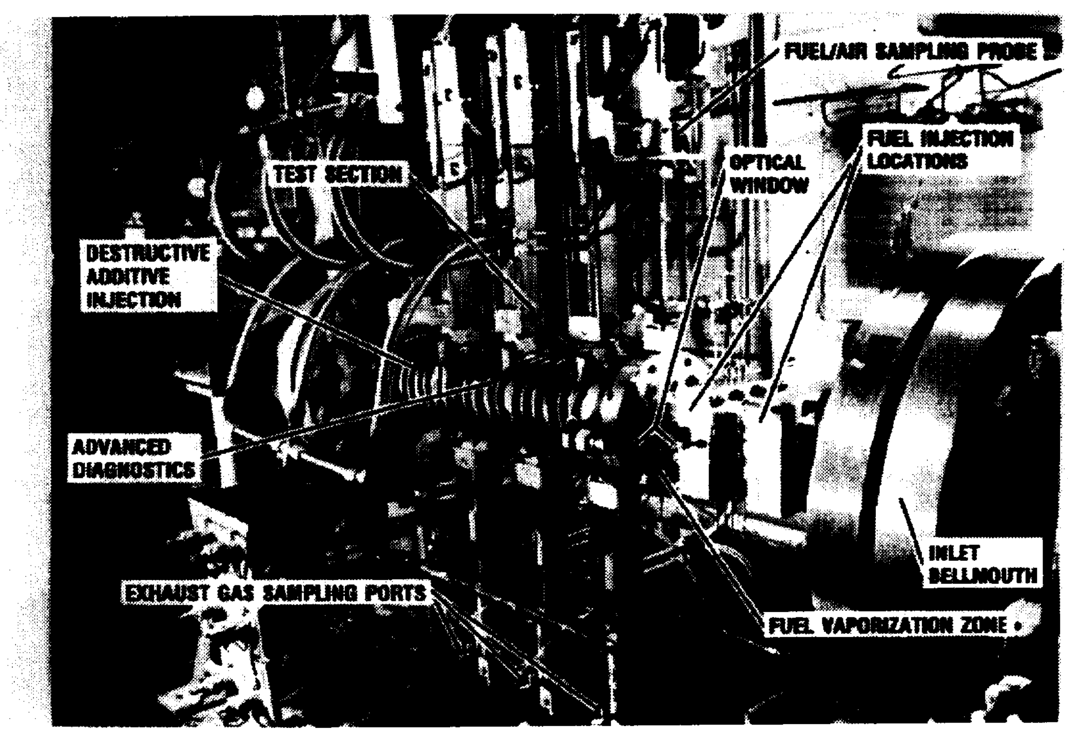


Figure 12 Combustion Flame Tube Test Setup

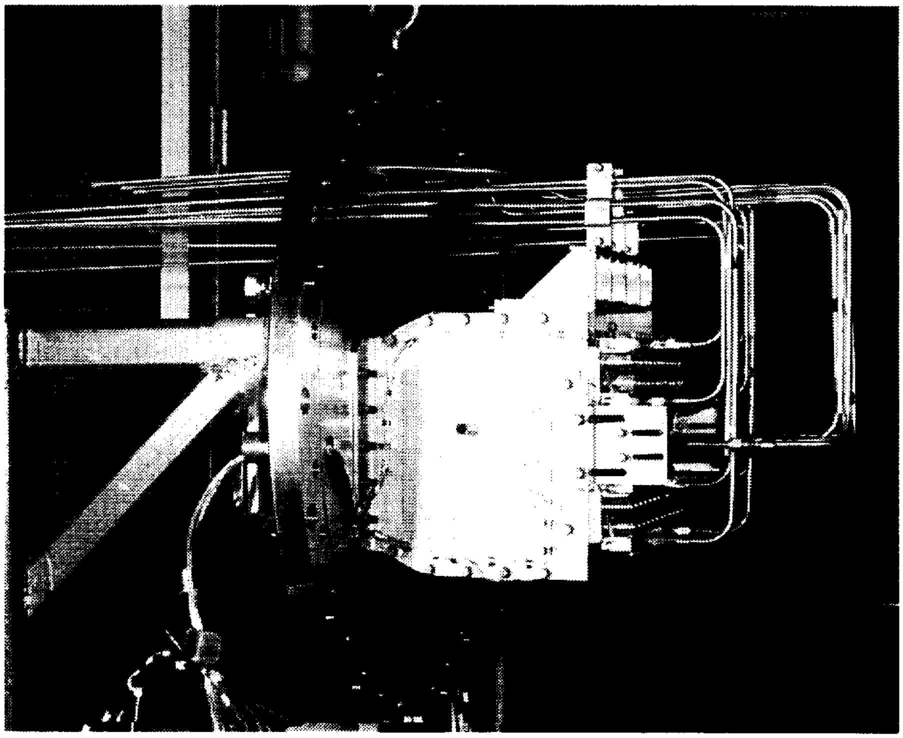


Figure 13 Combustor Sector Test Setup

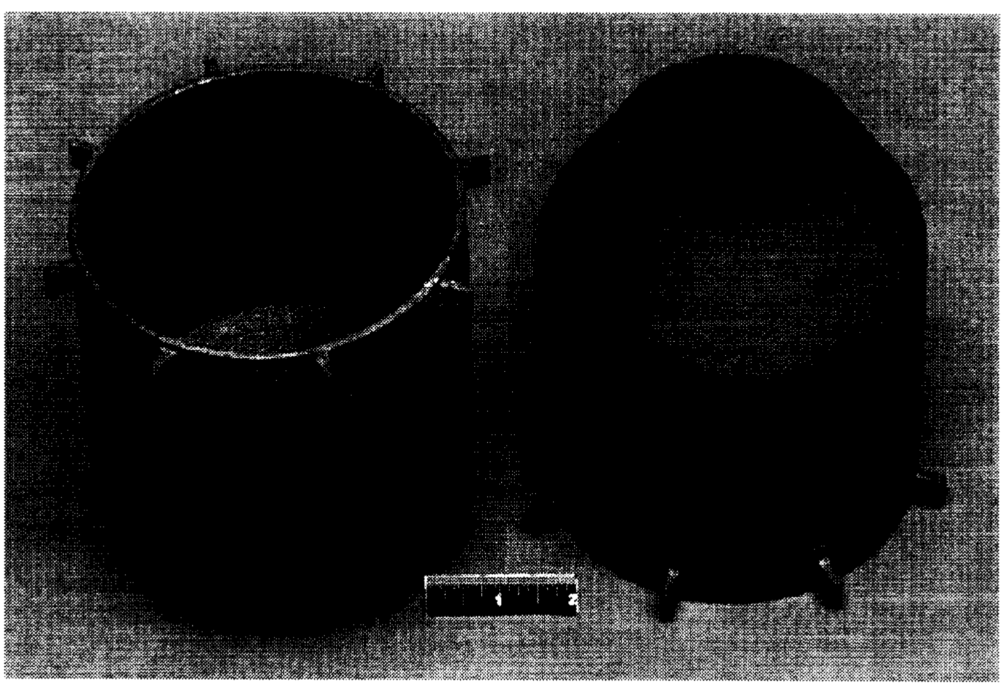


Figure 14 Fabrication of Complex Shape from SiC based Ceramic Matrix Composite

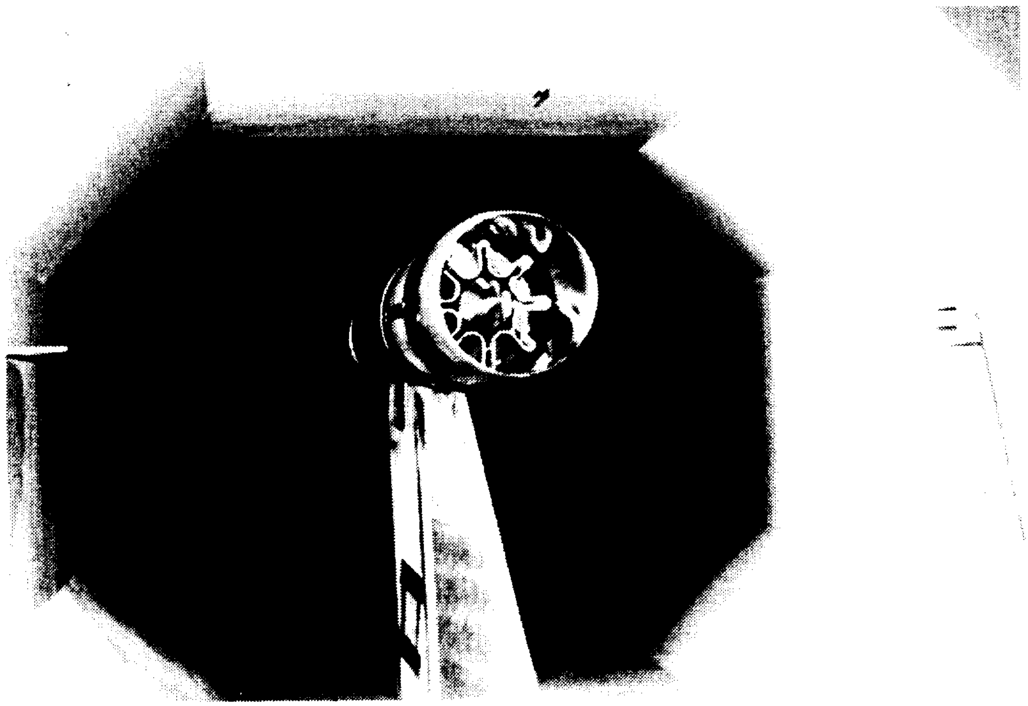


Figure 15 Nozzle Subscale Tests Setup

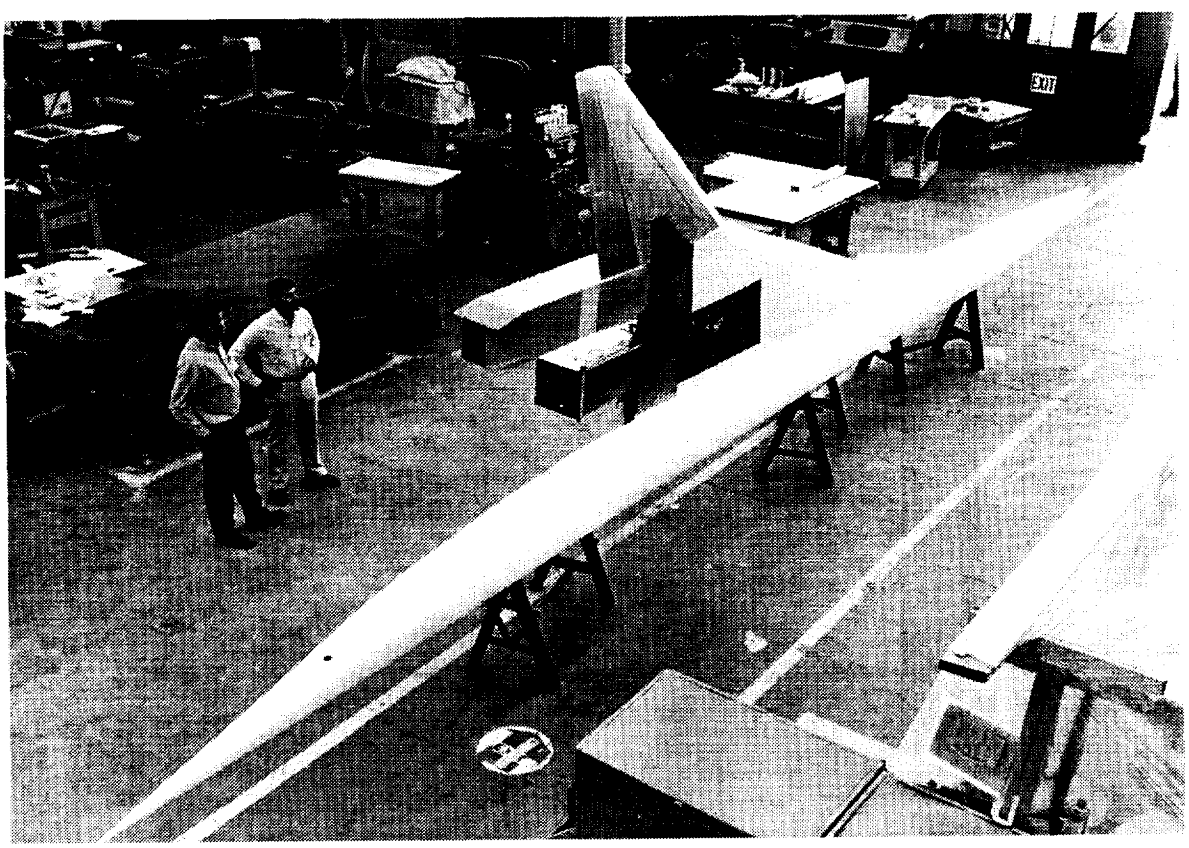


Figure 16 Propulsion Airframe Integration Test Model

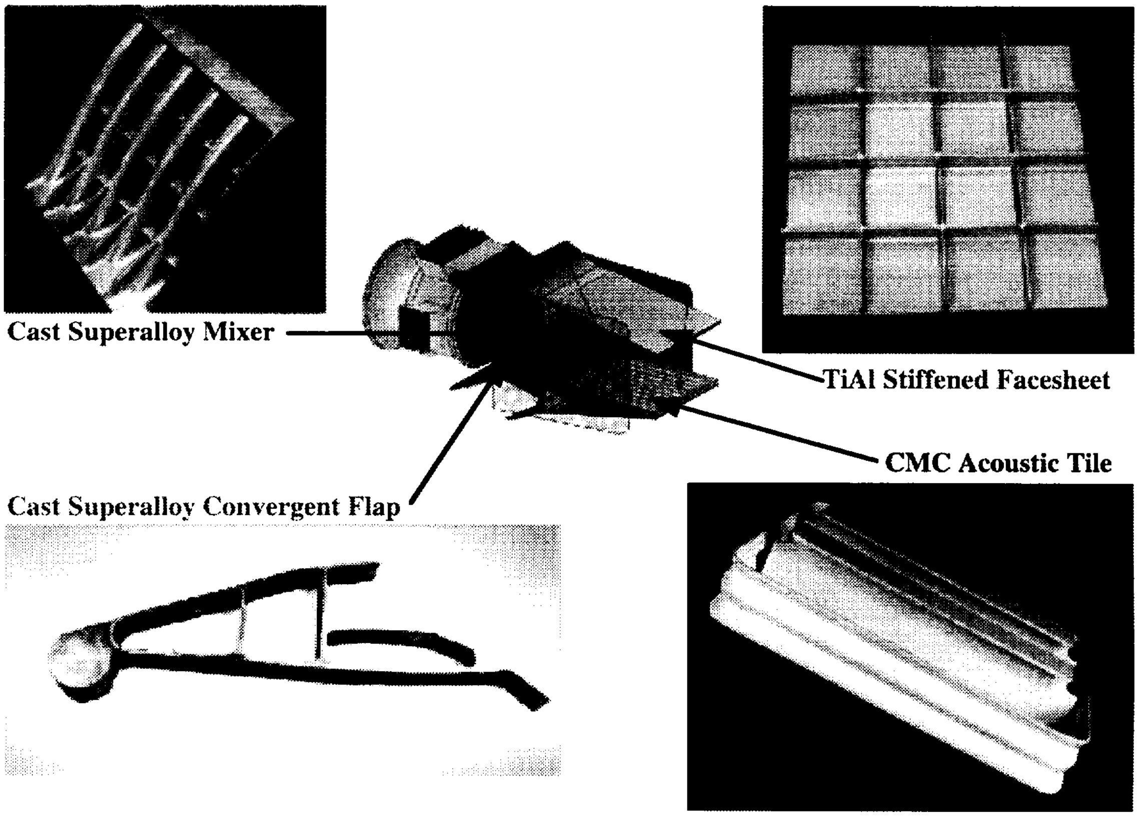


Figure17 Exhaust Nozzle Subelements Fabricated for Testing

HSCT Airfoil Alloy Developed

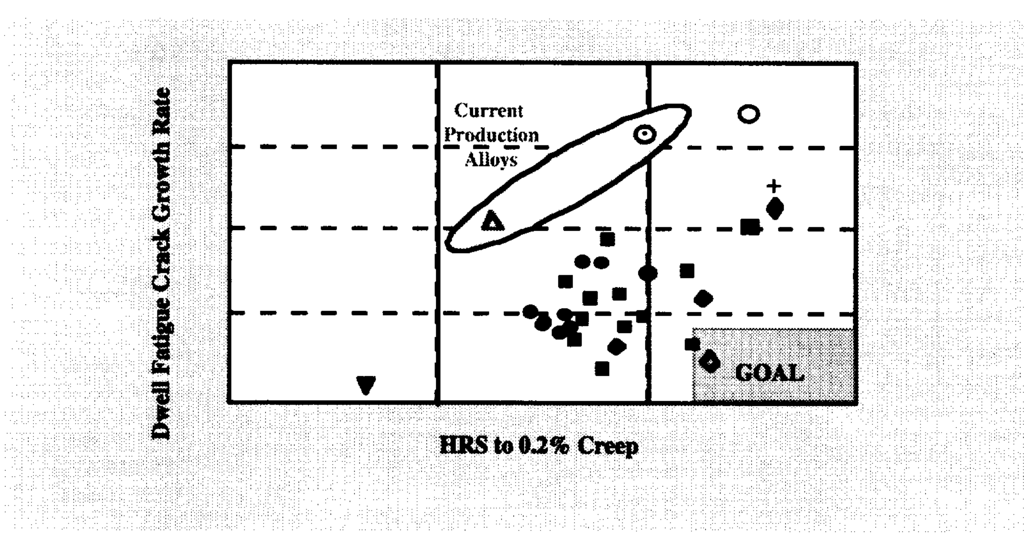


Figure 18 Status of development of advanced turbomachinery disk alloy

HSCT Airfoil Alloy Developed

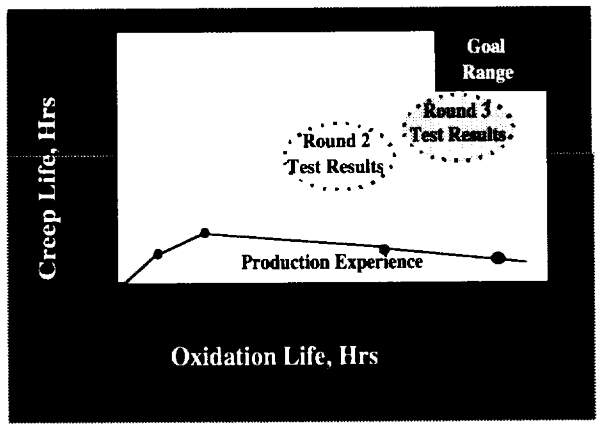


Figure 19 Status of development of advanced turbine airfoil alloy

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1997	Technical Memorandum

4. TITLE AND SUBTITLE

Progress Toward Meeting the Propulsion Technology Challenges for a 21st Century High-Speed Civil Transport

5. FUNDING NUMBERS

WU-537-05-23-00

6. AUTHOR(S)

Robert J. Shaw, Leigh Koops, and Richard Hines

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E-10915

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-113161
ISABE-97-7045

11. SUPPLEMENTARY NOTES

Prepared for the XIII International Symposium on Air Breathing Engines sponsored by the American Institute of Aeronautics and Astronautics, Chattanooga, Tennessee, September 8-12, 1997. Robert J. Shaw, NASA Lewis Research Center; Leigh Koops, General Electric Aircraft Engines, Evandale, Ohio 45249; Richard Hines, Pratt & Whitney Aircraft, Hartford, Connecticut 06108. Responsible person, Robert J. Shaw, organization code 2300, (216) 433-7135.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 01

This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.

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13. ABSTRACT (*Maximum 200 words*)

Ongoing NASA-funded and privately funded studies continue to indicate that an opportunity exists for a second generation supersonic commercial airliner, or High-Speed Civil Transport (HSCT), to become a key part of the 21st century international air transportation system. Long distance air travel is projected to increase at about 5 percent per annum over the next two decades. This projection suggests that by the year 2015, more than 600, 000 passengers per day will be traveling long distances, predominantly over water. These routes would be among the most desirable for an HSCT as part of the international air transportation system. Beyond the year 2000, this portion of the air transportation market is projected to be the fastest growing segment. The potential market for an HSCT is currently projected to be anywhere from 500-1500 aircraft over the 2005-2030 time period. Such an aircraft fleet size would represent a considerable share of the potential large aircraft market. However, the projected HSCT fleet size is very sensitive to a number of factors including the level of available technology. The technologies employed in any commercial aircraft design must improve product performance but not at the expense of significantly increased costs (acquisition, operation, and maintenance). Simply stated, the HSCT will be a technology driven airplane. Without significant advances in airframe and propulsion technologies over the levels currently available, there will be no second generation supersonic airliner! In order for the HSCT to become a reality, the technologies developed must contribute to an aircraft design which is (1) environmentally compatible and (2) economically viable. This paper will briefly describe the propulsion technology challenges which must be met prior to any product launch decision being made by industry and the progress toward meeting these challenges through NASA's High-Speed Research (HSR) Program, a partnership between NASA and Boeing, McDonnell-Douglas, General Electric, and Pratt & Whitney.

14. SUBJECT TERMS

High speed civil transport; Supersonic propulsion; Environmental compatibility; Economic viability; Component tests

15. NUMBER OF PAGES

18

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	