NASA/TM—1999-209193

Progress Toward National Aeronautics Goals

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Prepared for the
14th International Symposium on Air Breathing Engines
sponsored by the International Society for Air Breathing Engines
Florence, Italy, September 5–10, 1999

National Aeronautics and
Space Administration

Glenn Research Center

June 1999

Acknowledgments

This paper was prepared with help from the entire Aeronautics team at NASA Glenn Research Center. Pat Webb, Kathryn Kafantaris, and Caroline Rist were of special help in preparing this manuscript.

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PROGRESS TOWARD NATIONAL AERONAUTICS GOALS

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Abstract

NASA has made definitive progress towards achieving several bold U.S. goals in aeronautics related to air breathing engines. The advanced technologies developed towards these goals span applications from general aviation to large subsonic and supersonic aircraft. The proof of successful technology development is demonstrated through successful technology transfer to U.S. industry and projected fleet impact. Specific examples of progress are discussed that quantifies the achievement towards these goals. In addition, a more detailed vision for NASA aeronautics is defined and key strategic issues are explored. These invite international and national debate and involvement especially in reduced environmental impact for subsonic and supersonic aircraft, dramatic new capabilities in general aviation engines, and reduced development cycle time and costs.

Introduction

At the last ISOABE conference in 1997, Reference 1 discussed the new national aeronautics goals recently developed by NASA and the significant role propulsion systems play in achieving these goals. The goals are reiterated in Figure 1 for convenience. This paper discusses the recent progress made towards these goals in propulsions systems. The paper also describes a long-term vision for ensuring the environmental compatibility of aviation to ensure the growth in aviation, an integrated small air transportation system to bring door-to-door automotive convenience to commercial air travel, and an intelligent synthesis environment for a new culture in the design and development of large complex engineering systems.

For each of these goals, NASA has recently completed national roadmaps showing existing and future programs required to meet these goals including those at other agencies who are essential partners to progress such as the FAA and DoD. The roadmap for emissions is shown as an example in Figure 2. The national aeronautics goals are expressed in terms of ultimate impact while NASA's role carries technologies in aeronautics only to Technology Readiness Levels (TRL) of 6 as defined in Figure 3. Thus, NASA must partner with other government agencies, industry, and academia to effect the final result.

The need for collaboration extends well beyond the borders of the United States. As will be discussed, the challenges to aviation of reducing global climate impact to ensure the continued growth of aviation will require increasing levels of international cooperation and collaboration. Accomplishing collaborations internationally will be made more difficult by the increasing competitive advantage of propulsion systems with reduced noise and emissions. A vision for 10, 25 and 30-40 year goals in emissions reduction is discussed which could stimulate international discussions leading to a harmonization of goals and eventually closer working relationships.

Several major programmatic changes have taken place over the past six months. The Advanced Subsonic Technology (AST) and High Speed Research Programs (HSR) will end this fiscal year. A new propulsion program, Ultra Efficient Engine Technology Program, is proposed to start in fiscal year 2000. The impact of these programmatic changes on progress toward the national aeronautics goals will be discussed.

Progress

Overview

This section discusses the progress made in the past few years towards achieving the eight aeronautics goals. Safety has been an area of research for over forty years at NASA Glenn Research Center principally focused on icing. Accurate computer models have been developed to predict icing shapes on wings, tail surfaces, and engine inlets, the impact on performance of ice, and validating these predictions in the world's largest icing research tunnel and in research aircraft flying in actual icing conditions. Airspace capacity improvements are discussed only in the context of reducing engine noise with resulting reductions in noise abatement routes in the short term and with the potential of tripling capacity long-term by the elimination of noise curfews. Significant progress has also been made in reducing emissions from large subsonic and regional jet aircraft engines by 50% compared to 1996 ICAO Standards and in demonstrating emissions levels for a High Speed Civil Transport (HSCT) engine low enough to avoid impact on ozone in the atmosphere. Noise levels of subsonic engines have been reduced by 3 dB in the Advanced Subsonic Technology Program from 1997 levels and the aggressive noise goals of the HSCT engine was demonstrated as achievable in sub-scale fan and nozzle tests.

Improvements in the affordability of aircraft engines have been accomplished principally in reduced fuel burn and lighter weight engines. The feasibility of reduced travel time to Asia using a HSCT has been clearly demonstrated. The High Speed Research Program has met all of its aggressive engine goals before the program concludes this fiscal year. The General Aviation Propulsion (GAP) Program has

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successfully run both the low cost turbine and intermittent combustion engines needed to revitalize this industry. Finally, significant progress has been made in reducing the time to design and develop engines through advanced computer models of compressors and progress in developing the Numerical Propulsion Simulation System, a numerical test cell for engines that has demonstrated dramatic reductions in the time and cost to develop engine components.

Aviation Safety

To significantly improve the safety of aeropropulsion systems, major advances were made in the areas of icing, development of crack resistant materials, and crack detection. An overview of some of the high potential technologies is provided in this section.

Aerodynamic Measurement of Iced Surfaces—Measurement of aerodynamic characteristics of iced surface in a wind tunnel is a cumbersome process. It involves making a mold and then a casting of the ice shape, followed by instrumenting the casting, and testing at condition. This process can take months. During 1998, the world's first application of pressure sensitive paint (PSP) on ice accretions was successfully demonstrated. The paint adheres to glaze, rime and mixed ice and cures in three minutes at -10 °F. It retains detailed surface features and responds to pressure changes. With PSP, the process aerodynamic measurement of iced surface can be reduced to minutes. Data obtained from these tests is used to improve the Glenn Research Center (GRC) developed Ice Accretion code, LEWICE, ultimately to improve the safety of air travel.

Crack Resistant Materials for Compressor and Turbine Disks—An important objective of the Crack Resistant Materials research, which is currently being conducted at GRC, is to enhance the durability and design lives of high-pressure compressor and turbine disks. The overall goal of this research is to develop a reliable life prediction model.

Recent research effort at GRC on production quality powder metallurgy UDIMET 720 disk has established that oxide inclusions and large grain porosity (Figure 4) limit the fatigue life of disks. In addition it has been demonstrated that there is a close correspondence between the cyclic mean stress and the type of defect at which a fatigue crack will nucleate. Thus a high mean cyclic stress is likely to initiate failures at oxide inclusions. The result of this NASA research will be coordinated with the FAA, the engine companies, and Southwest Research Institute, San Antonio, Texas.

Propulsion System Health Management—A major effort is underway at GRC to develop and demonstrate technologies that can predict, detect, and prevent safety-significant propulsion malfunctions. Particular emphasis is being placed in the areas of advanced diagnostic/prognostic instrumentation for in-situ engine operation, advanced health monitoring algorithms for safety significant fault prediction/detection, and fault accommodating control logic to prevent or mitigate the effects of propulsion malfunctions.

Recent advances in this area include conceptual development of integrated diagnostics and controls for engine surge prevention and mitigation, and advanced instrumentation for detention of cracks in turbomachinery.

Integrated Diagnostics and Controls— Figure 5 shows the Integrated Diagnostics and Controls for Surge Prevention and Mitigation concept which aims to build upon previous Performance Seeking Control (PSC) efforts. It consists of an on-board model-based tracking filter which monitors engine instrumentation to track and quantify the effects of component degradations on fan and compressor stability margin. Control reconfiguration logic will utilize this information to update control schedules to insure adequate stability margin is maintained during transient operation to prevent engine surge events. The engine health information collected on-board can also be provided to ground-based diagnostic systems to support maintenance scheduling. The safety benefits of this technology are a reduction in rejected takeoff events due to engine surge, and a reduction of in-flight engine shutdowns. Secondary benefits include real-time tracking of engine component health to support on-condition maintenance, and optimized engine performance and emissions in the presence of degradation. A similar concept for improving engine stability was successfully applied to Pratt & Whitney, F100 engine. It is described in the section titled "Reduced Skin Friction Drag Through Micro-Blowing" of this paper.

In-Situ Crack Detection—The goal of the Advanced Turbomachinery Crack Detection Instrumentation effort is to develop and demonstrated instrumentation for in-situ crack detection as well as life and usage monitoring of critical engine components.

Application of thin film strain gages is an example of the recent advancements in in-situ crack detection technologies. This technology, shown in Figure 6, is minimally intrusive, and has been demonstrated to be robust and accurate in high temperature environments. Efforts are currently underway to develop two new technologies, *smart coatings and a unique ultrasonic technique.* The latter technology can detect significantly smaller cracks than previously considered possible. The safety benefits of this advanced instrumentation will be to reduce un-contained engine failures, and reduce in-flight engine shutdown events. Secondary benefits of this technology include a reduction in engine inspection times, the support of component life and usage monitoring to extend component Time Before Overhaul (TBO).

Emissions

Emission reduction research has been focused on NOx for both subsonic and supersonic engines. NOx levels have been demonstrated at 50% of 1996 ICAO Standards for large subsonic aircraft engines and 50% for regional jet engines. Figure 7 shows the AST combustor sector test results meeting the AST Program goal for large engine combustors. Figure 8 shows the progress made compared to current and proposed NOx levels regulated by International Civil Aviation

Organization (ICAO). These NOx reduction levels have been demonstrated to Technology Readiness Levels of 6 as defined in Figure 3. Some engines recently entering service have incorporated reduced emission technologies develop in the NASA AST Program.

This early introduction of the AST reduced NOx combustor technology enabled the United States to successfully negotiate a viable lower level of reduced emissions in recent ICAO meetings leading to the CAEP 4 agreements shown in Figure 8. The CAEP 4 agreements will further reduce NOx levels of the aviation fleet which is very important given the projected growth of aviation of 5% per year leading to a doubling of the fleet size by 2020.

In supersonic civil engines, emissions index reductions of a factor of 10 below State of the Art for supersonic engines have been demonstrated in realistic engine combustor geometries for an HSCT. A Lean, Pre-mixed, Pre-vaporized (LPP) combustor concept was downselected as the best solution to EI (Emissions Index) levels at or below 5 winning over the Rich-burn, Quick-quench, Lean-burn (RQL) combustor concept as shown in Figure 9. Additional information on the progress made in the HSR Program can be found in Reference 2.

Noise

A 3 dB reduction in subsonic engine noise has been demonstrated in the AST Program through the development of optimal swept fan blade and leaned stator designs. Numerical predictions were accurately made using advanced fan noise models and verified in the 9x15 wind tunnel at NASA GRC in a 22 inch rotating fan as shown in Figure 10. This successfully demonstrated a top level milestone in AST.

Further noise reduction work is continuing through fiscal year 2001 to meet the total engine reduction goal of 6 dB. When combined with aircraft noise reductions and reduced community noise impact through improved airspace operations, a total reduction of 10 dB will have been demonstrated from 1997 levels by 2007. These dB reductions are for single aircraft events. As these quieter aircraft enter into service (possibly 5-6 years after demonstration at TRL of 6 if market conditions warrant), the community noise impact will be reduced by 5-7 dB DNL (Day Night Level) by 2022 and then will rise again due to projected increases in aircraft traffic. The project growth in air travel necessitates continued development of reduced noise technologies as discussed further in the section titled "Visions for the Future" of this paper. This section also discusses the contributions to improvements in airspace capacity due to long-term noise reductions of 20 dB from 1997 levels.

In the HSCT, noise levels were demonstrated in sub-scale nozzle and fan tests at 5 dB below Stage 3 which is 25 dB below that of the Concorde. Figure 11 shows the nozzle results indicating the feasibility of meeting the HSR noise goals which are particularly challenging for the very large size of the nozzle coupled with a light weight, long life nozzle design. With the recent announcement by Boeing that a HSCT potential launch decision would be delayed from 2007 to around 2025, it became clear that the aggressive noise reduction technologies demonstrated in the HSR program would not be sufficient to meet projected noise levels in 2025. New engine designs and noise reduction technologies would be required. Reference 2 gives additional information.

General Aviation Propulsion

The General Aviation Propulsion (GAP) Program goals were to demonstrate revolutionary advancements in turbine and intermittent engines for the four to six seat aircraft class to enable a revitalization of this industry. Figure 12 shows the magnitude of the performance and cost improvement goals for the Williams International FJX-2 turbine in both turbine and turboprop configurations and the Teledyne Continental intermittent combustion engine. These advancements are achieved through simplified designs with greatly reduced parts, advanced casting and manufacturing technologies, and advanced aerodynamic designs. Both engines have been assembled and successfully run. Full performance data is not yet available but initial results are promising. Both engines will be flown at Oshkosh in the year 2000.

GA aircraft manufacturers are partners in the GAP program with the engine manufacturers and will be evaluating the performance improvements for aircraft with these engines. A turboprop version of the FJX-2 engine is also being developed under GAP to increase the market for these engines and help to reduce cost with increased volume. Derivative applications in marine, ground power, and rotorcraft are expected to further increase the market for these engines further reducing the price.

Affordable Air Travel

Several propulsion system related technology initiatives are underway to make the air travel more affordable. Primary focus has been on improving the performance (fuel burn and engine stability) and reducing the design and development cost. Development of high fidelity design and analysis tools, which directly help to improve engine efficiency and reduce design and development cost, is presented in the section titled "Design Tools and Experimental Aircraft" of this paper. Other technology areas that can have significant positive impact on performance and cost include smart control systems and advanced flow management concepts. Recent accomplishments in the areas of advanced concepts are described in the following paragraphs.

Smart Engine Controls—NASA recently concluded flight demonstrations of an advanced high-stability engine-control (HISTEC) system that is expected to significantly increase future propulsion system performance in both military and commercial aircraft turbine engines. The system, called Distortion Tolerant Control, incorporates an aircraft-mounted, high-speed processor that senses changes in airflow at the front of the engine and allows the system to automatically command trim changes to the engine to accommodate changing distortion conditions (Figure 13). This allows the engine to operate with more stability under adverse or turbulent airflow conditions. The HISTEC system was successfully flight tested at the Dryden Flight Research Center on modified F15 jet. Project pilots flew through a variety of maneuvers designed to create unstable or distorted airflow conditions in the engine air inlets, including flight angles up to 25 degrees, full rudder sideslips, wind-up turns, split-S descents, and simulated flight maneuvers.

The primary benefit of Distortion Tolerant Control is that it can allow the built-in stall margin to be reduced, which can then be traded for increased performance, decreased weight, or both. The result will be higher performing and more fuel efficient aircraft producing less emissions.

Reduced Skin Friction Drag Through Micro-Blowing—The Micro-Blowing Technique (MBT), an innovative method for reducing skin-friction, was invented in 1993 by researchers at the Glenn Research Center. MBT is a unique concept in which an extremely small amount of air is blown vertically through a specially designed porous plate with micro holes. This reduces the surface roughness and viscous shear drag, thereby reducing skin friction. In September 1997, a joint program of GRC, United Technologies Research Center, Northrop Grumman Corporation, and Pratt & Whitney was completed. In this program, a 30-inch engine nacelle with an MBT skin was tested in United Technologies' wind tunnel (Figure 14). The results indicated that 50 to 70% reduction in skin friction are possible over portions of nacelle, with the addition of only small amounts of blowing air. This technique when applied to other aircraft surfaces can result in substantial reduction in drag, which in turn will result in reduced fuel burnt.

Affordable, Light Weight Materials—Glenn Research Center has recently succeeded in developing a low cost, light weight material under the High Temperature Engine Materials and Structures Project (HITEMP) program for application in engine cold section. AMB-21 was used to fabricate a surge duct for AlliedSignal 331-500 Auxiliary Power Unit, which is used on Boeing 777. When compared to the currently used titanium duct, this duct costs 25% less to fabricate, is 30% lighter in weight, and has six times the durability (Figure 15). Reduced APU weight directly helps in reducing the fuel burnt. Use of this material for fabrication of other engine cold section components, such as the compressor case, can result in significant saving in manufacturing cost, fuel burnt (due to reduced weight) and maintenance cost.

Design Tools and Experimental Aircraft

NASA GRC is leading a Government-Industry cooperative effort under its Numerical Propulsion System Simulation (NPSS) program directed at developing a system that can perform aero-thermo-structural numerical simulation of a complete air-breathing gas turbine engine. The goal is to reduce the engine design and development time by a factor of two and also help to improve engine performance and durability. Major advances have been made beyond the axisymmetric full engine simulation shown in Figure 16. Some of the recent accomplishments in the area of advanced design/ analysis tools and flow measurement techniques for validation of these tools are discussed in more detail.

Engine Design/ Analysis Tools

Modeling of aerodynamic interactions among turbomachinery blade rows—The APNASA (Average Passage NASA) code, which simulates viscous, unsteady interactions effects among blade rows, was used to perform simulation of GE90 compressor and turbine on a cost-effective work station cluster. The results obtained from this simulation are being compared to the experimental test data to validate the code. Several engine companies are currently using APNASA to design rotating components for their next generation engines.

High Speed Computing—A 200:1 reduction in the time to perform a 3-D reacting flow simulation of a gas turbine combustor on a cluster of SGI Origin 2000 processors was demonstrated. This now enables large scale combustor problems (in excess of 1 M grid points) to be solved in less than 15 hours.

Common Thermodynamic Analysis—The first version of National Cycle Program (NCP), which can help to significantly increase productivity in the preliminary design of propulsion systems and its integration with airframes, was released to aeropropulsion industry. The advanced software design and object-oriented structure provide a framework to extend modeling capabilities to include high fidelity, multidisciplinary system analysis in a collaborative environment.

Unsteady Coupled Aero-Structure Simulation— NASA GRC-Mississippi State University developed TURBO-AE code, which couples a three-dimensional unsteady aerodynamic Euler/Navier-Stokes model with a finite-element structural dynamics model, has been validated in collaboration with four engine companies. The validation was performed using standard configuration data, NASA data, and engine company data. In addition, code-to-code comparisons were performed using existing lower fidelity codes from NASA and engine companies. As an example of the validation work, one engine company used TURBO-AE to accurately model observed fan rig flutter including the correct operating condition, flutter mode, and inter blade phase angle. A typical TURBO-AE prediction is shown in Figure 17.

Advanced Flow Measurement Techniques—In conjunction with advances in simulation tools, major advances have also been made in optical measurements of flow field. These measurements not only provide physical insight into fundamental physics but are also tied directly to code development, bringing us ever closer to virtual designs. Specific examples of accomplishments in the last year are described.

Particle imaging velocimetry (PIV)—The PIV, which is a pulsed laser sheet, was used to see inside complex machinery rotating at high speeds, capturing the world's first instantaneous planar velocity maps in a high speed (21,000 RPM) centrifugal compressor (Figure 18). These measurements captured transient surge events, showing details of both supersonic and reversing flows within the flow passage, yielding information useful for designing an active stall control system. Phase-resolved steady-state date from PIV was also used to add a splitter module to APNASA code.

Noise Measurement—Rayleigh scattering technique was recently used to measure the power spectral density in a Mach 1.37 jet, showing the evolution of noise sources along center line. This data is being evaluated to understand fundamental physics of noise generation and to validate computational aeroacoustics codes, leading to quieter aircraft.

Visions for the Future

NASA has developed dramatic visions for achieving the national goals. Three areas are discussed in this section: environmental compatibility, general aviation, and design and development environment. Not discussed but of vital importance is a vision for high speed civil aviation. With the termination of the HSR Program, it is important to assess the nation's needs in high speed civil aviation technologies particularly in propulsion since it is a long lead enabling system for any supersonic aircraft. A cohesive vision is needed for incorporating technologies needed for civil aircraft from bizjets to a HSCT, and for developing technology synergies with high speed military aircraft and air breathing access to space. This is a multi-agency effort that is essential to ensure the future competitiveness of the U.S. industry in both aeronautics and space.

Environmental Vision

The high level vision for aviation has been set by the White House Policy as documented in Reference 3 (NSTC August 1995 Goals for a National Partnership in Aeronautics Research and Technology). In addition to maintaining the superiority of US aircraft and engines and improving the safety, efficiency and cost effectiveness of the global air transportation system, the long-term environmental compatibility of the aviation system must be ensured. In particular, this reference states, "Past research investments in technologies to reduce engine noise and emissions are paying dividends today. But more needs to be done. Environmental issues are likely to impose the fundamental limitation on air transportation growth in the 21st century."

In addition, the National Research Council states in Reference 4: "The public will continue to demand reduction in environmental damage and reductions of acoustic noise over urban areas. This will require the United States to collaborate with other nations to develop technology that will reduce or eliminate harmful aircraft engine emissions and technology that will enable quieter engines and operations, including revolutionary means to mitigate sonic boom effects over populated areas."

The priority of environmental compatibility is also an increasingly important competitive advantage internationally. The European Commission has highlighted engine emissions and noise reductions as key technology areas for funding in aeronautics research. Thus, environmental compatibility is recognized by many policy making and research organizations as a major barrier to the projected growth of aviation and the economic and physical health of nations and a principal area for research. The soon to be published United Nations Special Report on Aviation and the Global Atmosphere (Reference 5) is testimony to the importance of reducing emissions from aircraft and will be the definitive document for many policy-makers.

NASA has held a series of three national workshops over the past year involving major research, policy making, regulation setting, and stakeholder and community groups to develop a national consensus on the highest priority environmental compatibility goals and proposed technical approaches. The results of these workshops are available on the Environmental Compatibility Assessment (ECoA) web page: http://www.hq.nasa.gov/office/aero/oastthp/programs/encompat/encompat.htm.

Emissions—For emissions, three improvement areas were highlighted: global warming reversal, improved local air quality, and ozone depletion recovery. The highest priority emittants identified were CO_2 and NOx and the quantified metrics for these emittants are given in Figure 19.

The CO_2 metrics were driven principally by two factors: the ten and twenty five year metrics were what was judged as the best achievable by improvements to gas turbine based propulsion systems. The thirty to forty year goals were driven by the Kyoto Protocol. Figure 20 shows that aviation cannot fully meet the Kyoto Protocol requirements of 5% below 1990 levels by 2010. Also shown is the reduction in CO_2 emitted by aircraft if a zero emissions aircraft were introduced at various time frames. If zero emissions aircraft were developed and introduced beginning in 2027, the CO_2 emitted by aviation by 2045 would achieve reductions consistent with the Kyoto Protocol.

The long-term CO_2 metric spawned the concept of a zero emissions aircraft that also set the long-term NOx metrics. A very preliminary study was made at NASA of various zero emissions aircraft concepts. Liquid hydrogen powered aircraft are bigger but lighter than other concepts and present operational, airport infrastructure, and engineering challenges including storage of hydrogen in the fuselage. In addition, current methods of production of liquid hydrogen are very pollutive and do not represent a good option for overall CO_2 reductions. Liquid methane aircraft fall between kerosene fueled and hydrogen fueled aircraft offering modest reductions in CO_2 and NOx. Nuclear powered aircraft show the potential for greatly reduced CO_2 emissions with NOx reduction levels mixed and dependent on the weight of the shielding required. Safety and public acceptance issues would probably render the nuclear powered aircraft option undesirable.

The best concept appeared to be a fuel cell powered aircraft offering true zero emissions depending on the source of hydrogen. The fuel cell concept used for this preliminary study is shown in Figure 21. The fuel cell is used to generate power for electric motors that drive fans and propellers using hydrogen fuel and assumes Proton Exchange Membrane (PEM) technology being spearheaded by the automotive industry for use in 5-10 years. The weight is projected to be about 10% lower than current State of the Art (SOA) gas turbine based systems. Some funding is planned in the NASA Propulsion Systems Base R&T Program lead by NASA GRC starting in fiscal year 2000 to further explore zero emissions aircraft propulsions system concepts.

The near-term NOx metrics were set by the NASA Three Pillar Goals as shown in Figure 19. A new program called the Ultra Efficient Engine Technology (UEET) Program is proposed to start in fiscal year 2000 which will demonstrate the 67% NOx reduction levels in realistic engine combustors but will fall short of demonstration in a fully integrated engine system. The UEET Program will also demonstrate fuel burn and CO_2 reduction levels of 8-15% at the component level. Again, a TRL demonstration in a fully integrated engine will not be undertaken in this program. Figure 22 shows the currently major investment areas and proposed metrics for UEET Program.

These metrics follow from the overall goals of this program. The UEET Program has three high level goals: (1) increased performance to enable and enhance a wide range of revolutionary aircraft for small to large and over a wide range of flight speeds, (2) address local air quality concerns and potential ozone depletion by developing technology for NOx emissions reduction at take-off and landing conditions, and also technology to enable aircraft to not impact the ozone layer during cruise operation, and (3) address long term aviation growth potential without impact on climate by providing technology for dramatic increases in efficiency to enable reductions in CO_2 as well as all of the other emissions. The UEET Program is currently being planned in greater depth in collaboration with U.S. industry and academia.

It is important to note that noise technology is not currently included in the UEET Program.

Noise/Capacity—Noise constraints on commercial air travel have escalated as shown in Figure 23. It is estimated that only 2 commercial service airports in the US have no noise restrictions. As with emissions, reduced noise engines are a rapidly increasing competitive advantage as well as an increasing cost to airline operations both in landing fees, reduced landing slots, and additional fuel burn during noise abatement routes. In addition, increasing impact on community noise will be a serious barrier to the growth of aviation even with the noise reductions gained in the AST Program discussed earlier. Figure 24 shows how the reduction in single aircraft noise is offset with time by the growth in air traffic which increases the noise impact at the airport boundary as measured by the Day Night Level (DNL).

This figure also shows the far term vision for noise reduction embraced by the ECoA workshops denoted as "Pillar 3" which is the 25 year goal. Meeting this goal means shrinking the 65 dB DNL contour to fall within the airport boundary thus reducing the community impact to a level that will not seriously impede the growth of aviation. Such a reduction would have profound effects on community noise and airspace capacity.

It is estimated that the resulting elimination of noise abatement routes would also save 2-4 minutes per flight leg saving the airlines billions of dollars per year. In comparison, the flight time savings goal of the NASA Aviation Capacity Program is 6 minutes per flight leg. There is the potential for the elimination of noise curfews which could increase the operating hours of the busiest airports with the potential of tripling airspace capacity through expanded hours and the use of existing alternate runways currently unusable for large commercial aircraft due to noise restrictions.

This level of noise reduction is another 10 dB below the level demonstrated in the AST Program and will require significant further reductions in engine, airframe, and operations noise levels. In the engine these reductions will be accomplished through further reductions in fan and jet noise, light weight installable ultra high by-pass ratio engines, low turbulence flow management, distributed exhaust streams, among other technologies.

The AST Program goal of 10 dB reduction in single aircraft noise will be demonstrated through 6 dB engine noise reduction, 3 dB airframe noise reduction, and 1 dB noise reduction through improved airspace operations. The AST Program will be terminated at the end of fiscal year 1999 but the noise work will be continued in the Base research programs. The AST noise reduction goal of 10 dB will be demonstrated by fiscal year 2001 although at a lower technology readiness level than 6 as previously planned.

Future Propulsion Systems for General Aviation

NASA is developing a new vision for the future of general aviation to address the barrier to the growth of aviation due to constrained airport capacity and mobility. This vision is called the Small Air Transportation System (SATS) and is shown pictorially in Figure 25. The approach is to achieve improvements in capacity and mobility by an integrated ground and air transportation system utilizing the thousands of small airports nationally currently underutilized and harnessing the advancements in satellite communications, global positioning, and weather information in the cockpit to enable dramatic improvements in mobility door to door.

The future of General Aviation is critically coupled with the future propulsion systems; that is, the propulsion systems will enable the next generation aircraft to be developed and deployed. The vision of General Aviation in the future is for an affordable, safe and efficient transportation system that would be utilized much as we currently use ground transportation. The system would be used by many more people and the take-off/landing locations would be numerous and close to homes and workplaces. Vertical-takeoff and landing (VTOL) aircraft shown in Figure 26, would play a prominent role in this personal transportation system.

In establishing the baseline General Aviation propulsion systems in use today, we have intermittent combustion (piston) engines for general use aircraft and turbine engines for very expensive business use aircraft. The IC engines are typically spark-ignition, 4-cycle, air-cooled engines. They use low-lead aviation gasoline, have at least two pilot control inputs, require continuous monitoring of several engine status gauges, and are expensive. The turbine engines are typically very expensive.

In reaching the vision for General Aviation, enabling aircraft propulsion systems will have to address several factors, including: cost, safety, ease of use, reliability, and environmental compliance.

The propulsion system such a vehicle could be either an IC or turbine based engine. Low cost will be achieved through advanced design and development processes, such as concurrent engineering, analytical development methods, rapid prototyping; innovative manufacturing processes; and low parts count. Even greater cost reductions will be possible with high volume production, driven by multiple applications, other than aviation, for the engines. Performance and durability will be improved through the use of new lightweight materials such as metal matrix composites, polymer matrix composites, and ceramics. Safety and ease of use would be enhanced through the use of "smart" systems using computers and artificial intelligence to both control the propulsion system and monitor its health and performance. Environmental compliance will be assured through the use of advanced combustion system and acoustical treatments.

For propulsion engines concepts beyond current engine types, radically different propulsion can be envisioned that use alternative energy sources such as an electric propulsion system with hydrogen fuel cells. The technologies to enable these types of engines, such as superconducting material motors and hydrogen fuel cells, are still in the research stage and will require several years to reach a readiness level for commercial implementation.

Intelligent Synthesis Environment

One of the goals of NASA's Next Generation Design Cycle is to reduce the design cycle for new commercial aircraft and engines by 50% within 10 years and 75% within 25 years, while increasing the design confidence. Reaching this goal will dramatically affect the cost of developing new propulsion systems that are fully integrated with aircraft. More recently, NASA has extended this vision to the entire "life cycle cost" of the product.

To meet this challenge, NASA has developed a concept referred to as the Intelligent Synthesis Environment (ISE). The ISE will represent a radical cultural change in the way that missions and engineering systems are currently developed. ISE will combine leading-edge technologies in computer science, computational intelligence, physics-based modeling, and other areas, to enable an engineering system to be modeled from "cradle-to-grave" in a virtual-reality environment. The system's total life-cycle will be simulated, starting with conceptual design, through other stages such as preliminary design, detailed design, manufacturing, assembly, mission performance, maintenance, repair and disposal. The ISE will link geographically dispersed mission synthesis team members, such as scientists, engineering design teams, technicians, manufacturers, suppliers, and consultants. Formed into a "virtual team," ISE will provide the intelligent simulation tools these individuals need to participate collectively in the synthesis of the missions within a high-performance team environment, and to participate in the creation and simulated operation of the aerospace systems that support the mission objectives. Reference 6 discusses the application of ISE to engine systems.

Summary

NASA has made significant progress towards many of the eight national aeronautics goals developed in 1998. Improvements in propulsion systems that are crucial to progress in seven of these eight goals in the areas of safety, emissions, noise, affordability, design cycle time and cost, general aviation, and high speed travel to Asia have all been demonstrated. Three of these goals namely noise, affordability, and high speed travel to Asia are currently at "parade rest" due to funding constraints.

A long-term vision has been discussed at a high level for environmental compatibility, design systems, and general aviation. Ensuring the continued environmental compatibility of civil aircraft is an international imperative for both the global and economic health of the world's nations and is a major barrier to the growth of aviation. Within NASA this area presents the greatest funding challenges in aeronautics. International cooperation sensitive to competition issues must dramatically increase if the global environment challenges to aviation are to be met in a viable timeframe.

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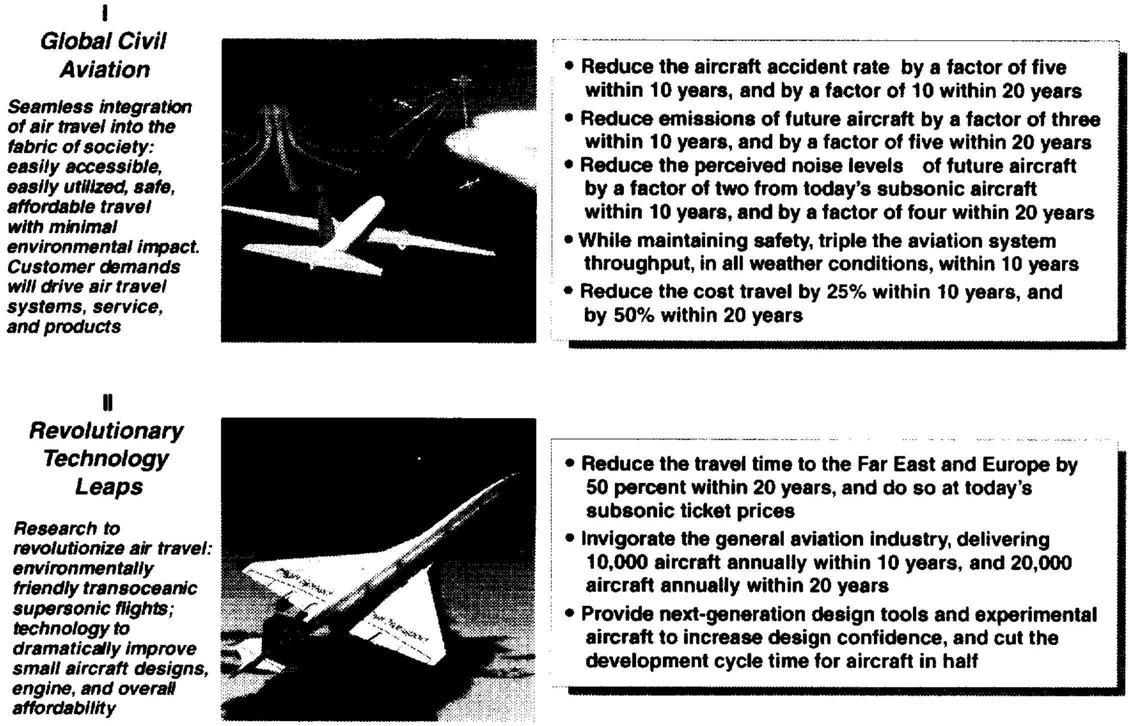


I

Global Civil Aviation

Seamless integration of air travel into the fabric of society: easily accessible, easily utilized, safe, affordable travel with minimal environmental impact. Customer demands will drive air travel systems, service, and products

- **Reduce the aircraft accident rate by a factor of five within 10 years, and by a factor of 10 within 20 years**
- **Reduce emissions of future aircraft by a factor of three within 10 years, and by a factor of five within 20 years**
- **Reduce the perceived noise levels of future aircraft by a factor of two from today's subsonic aircraft within 10 years, and by a factor of four within 20 years**
- **While maintaining safety, triple the aviation system throughput, in all weather conditions, within 10 years**
- **Reduce the cost travel by 25% within 10 years, and by 50% within 20 years**

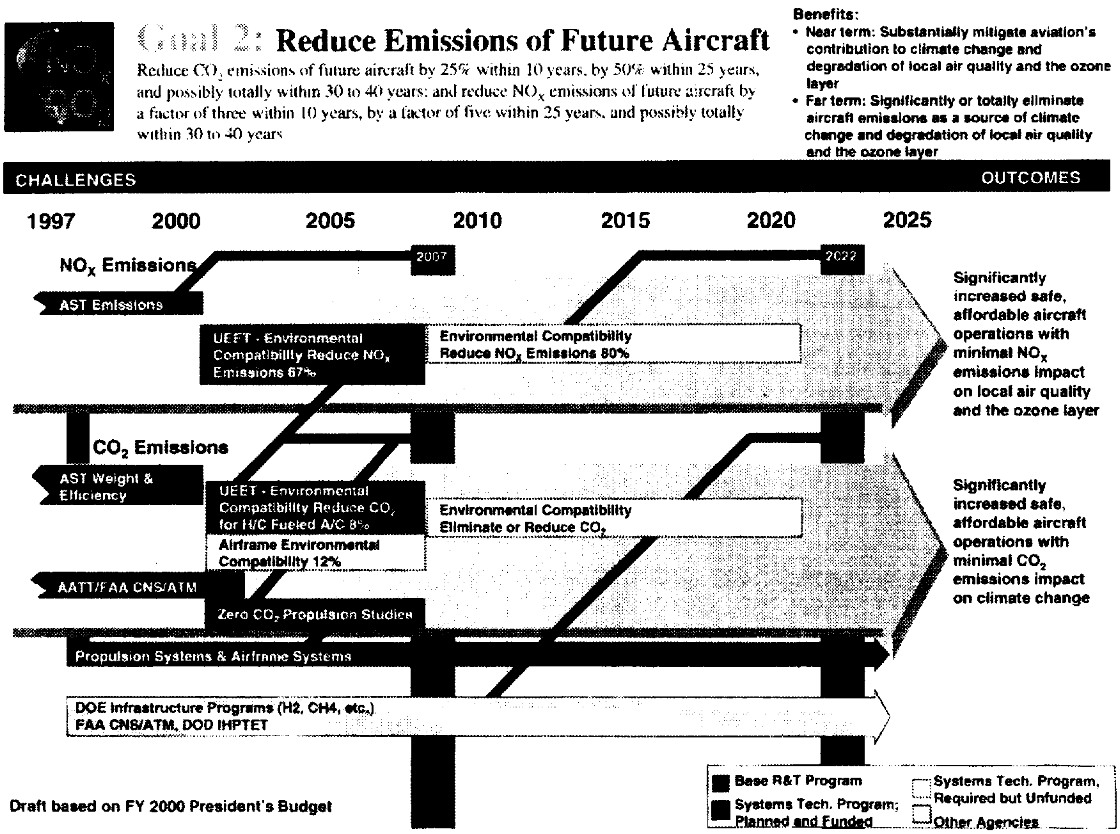
II

Revolutionary Technology Leaps

Research to revolutionize air travel: environmentally friendly transoceanic supersonic flights; technology to dramatically improve small aircraft designs, engine, and overall affordability

- **Reduce the travel time to the Far East and Europe by 50 percent within 20 years, and do so at today's subsonic ticket prices**
- **Invigorate the general aviation industry, delivering 10,000 aircraft annually within 10 years, and 20,000 aircraft annually within 20 years**
- **Provide next-generation design tools and experimental aircraft to increase design confidence, and cut the development cycle time for aircraft in half**

Figure 1.—NASA national aeronautics goals.



Goal 2: Reduce Emissions of Future Aircraft

Reduce CO_2 emissions of future aircraft by 25% within 10 years, by 50% within 25 years, and possibly totally within 30 to 40 years: and reduce NO_x emissions of future aircraft by a factor of three within 10 years, by a factor of five within 25 years, and possibly totally within 30 to 40 years

Benefits:

- **Near term: Substantially mitigate aviation's contribution to climate change and degradation of local air quality and the ozone layer**
- **Far term: Significantly or totally eliminate aircraft emissions as a source of climate change and degradation of local air quality and the ozone layer**

Draft based on FY 2000 President's Budget

Figure 2.—Goal 2: Reduce emissions of future aircraft roadmap.

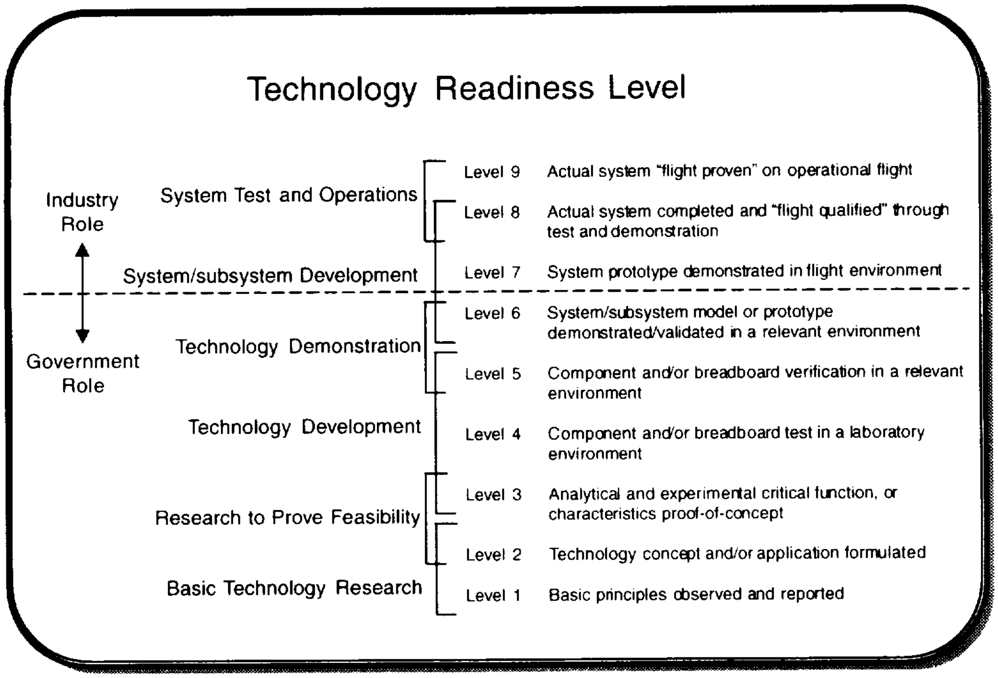
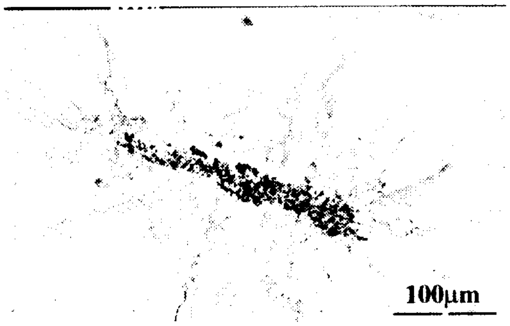
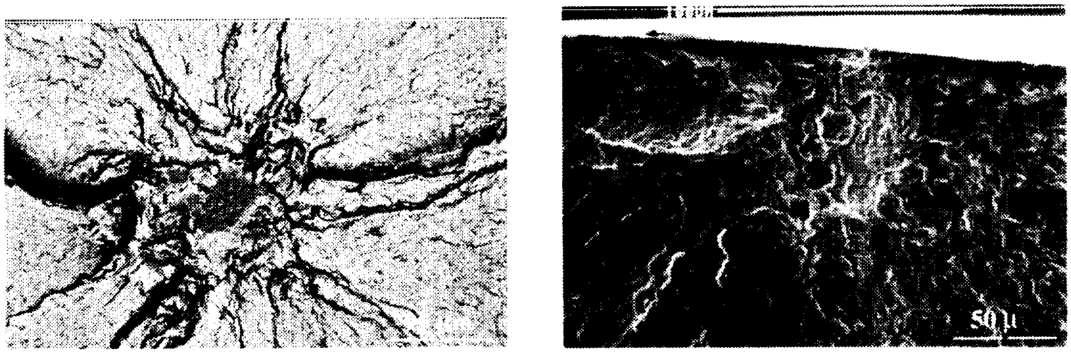


Figure 3.—Technology Readiness Levels definition.



Oxide Inclusions



Large Grains **Pores**

Figure 4.—Defects limiting the fatigue life of a PM disk superalloy identified.

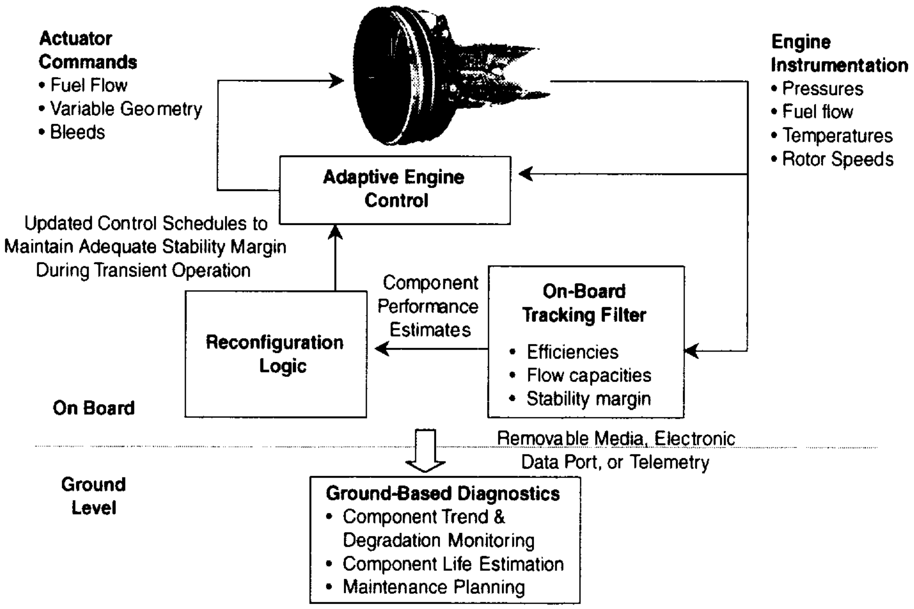
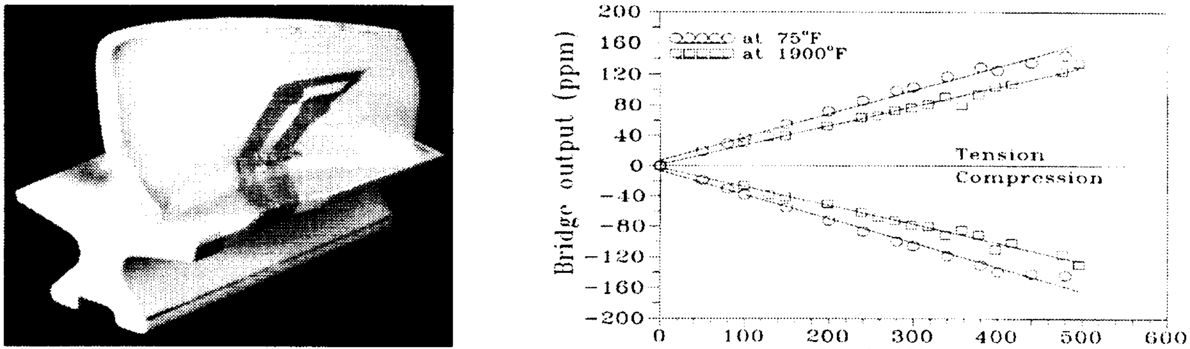


Figure 5.—Integrated Diagnostics and Control concept for surge free engine operation.



- Gages survived to a speed of 42500 rpm, under ±2000 microstrain up to 1000 °C for a million cycles
- Used on superalloys, ceramics, and composites

Figure 6.—High temperature thin film strain gage technology for crack detection demonstrated under high cyclic loads.

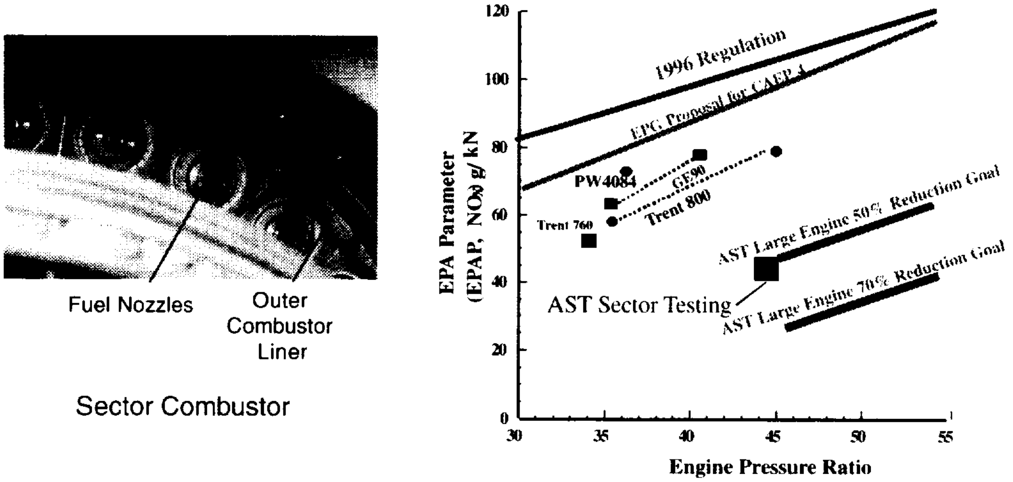


Figure 7.—50 percent NOx reduction low emission sector combustor demonstrated.

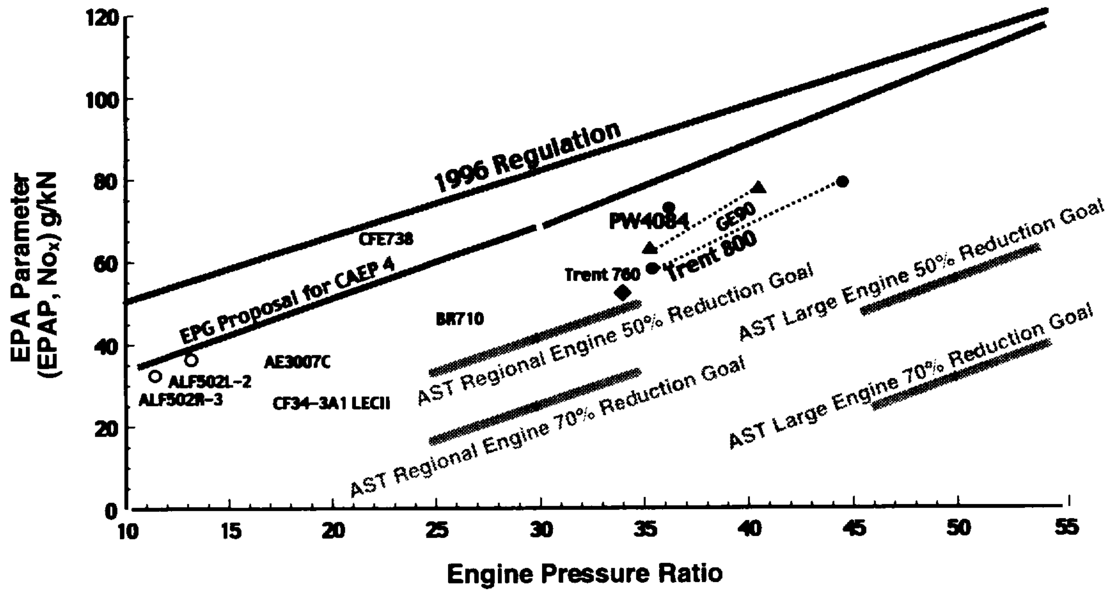


Figure 8.—NOx emissions characteristics, ICAO regulations, proposals, and NASA's AST goals.

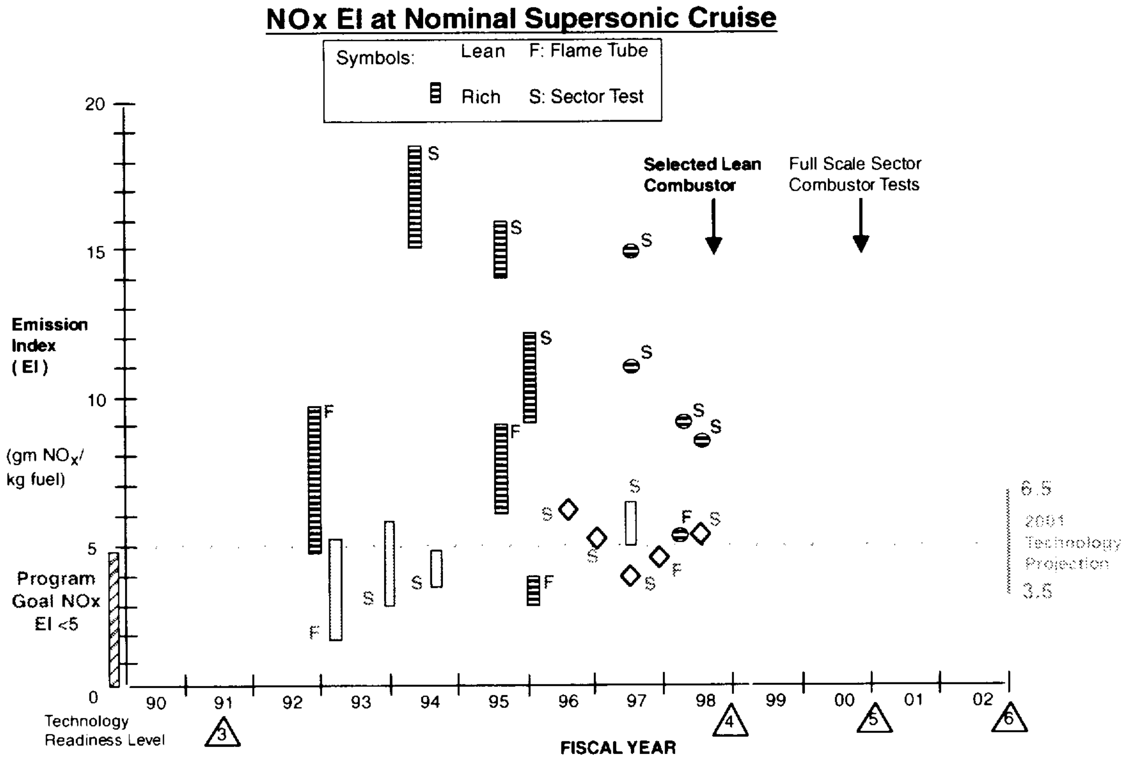
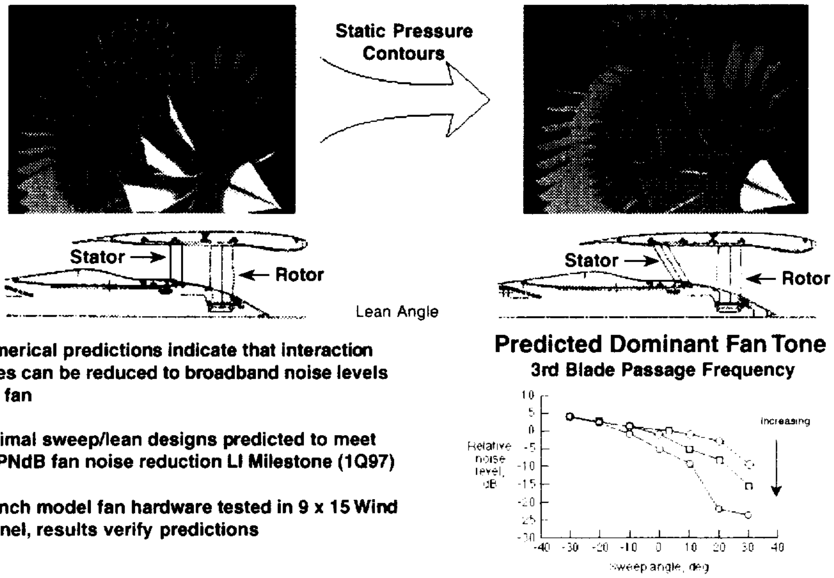


Figure 9.—Low Emissions Index demonstrated by HSR Program.



- Numerical predictions indicate that interaction tones can be reduced to broadband noise levels of a fan
- Optimal sweep/lean designs predicted to meet 3 EPNdB fan noise reduction LI Milestone (1Q97)
- 22 inch model fan hardware tested in 9 x 15 Wind Tunnel, results verify predictions

Figure 10.—Noise reduction milestone achieved in AST Program.

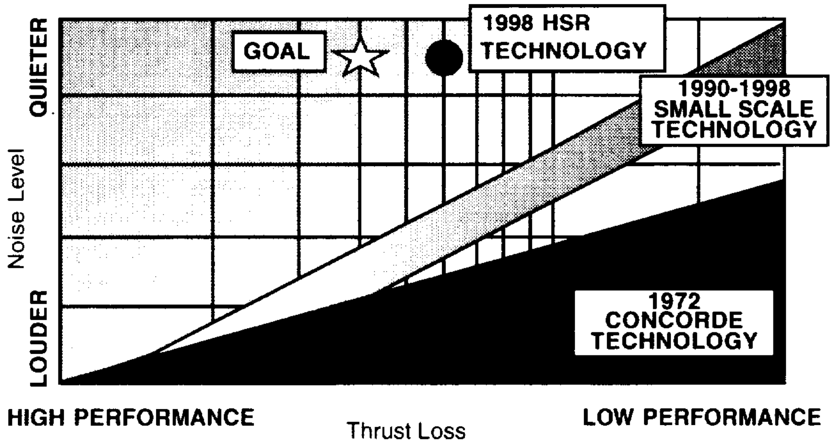
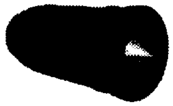


Figure 11.—Noise Reduction Milestone Achieved in HSR Program.


GAP Engine


FJX-2

210	Power (hp)	200
350	Weight (lb)	~ 350
Gasoline	Fuel	Jet
Air	Cooling	Liquid
0.45	bsfc	0.36
$30K	Cost	~$15K
1800	TBO (hr)	3000
Noisy & Harsh	Comfort	Quiet & Smooth

	Thrust (lb)	700
420	Power (hp)	~500
195	Weight (lb)	< 100
0.66	bsfc	< 0.5
$230K (+$30K)	Cost	~$65K
3500	TBO (hr)	5000
1750	Hot Sec. (hr)	2500


IO 360 ES


Allison 250-B17C Turboprop

Figure 12.—GAP Trend Setting Revolutionary Engines.

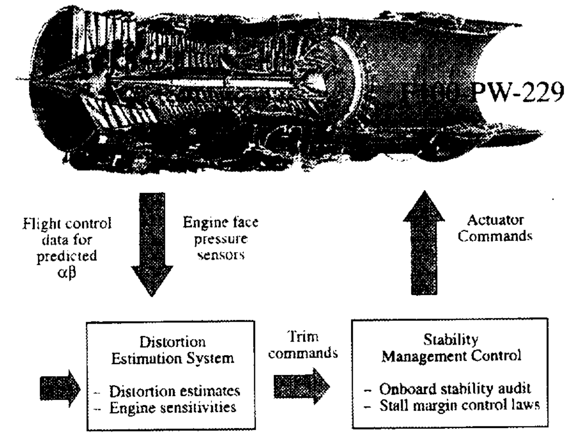


Figure 13.—Smart control system technologies being tested on the Pratt & Whitney engine.

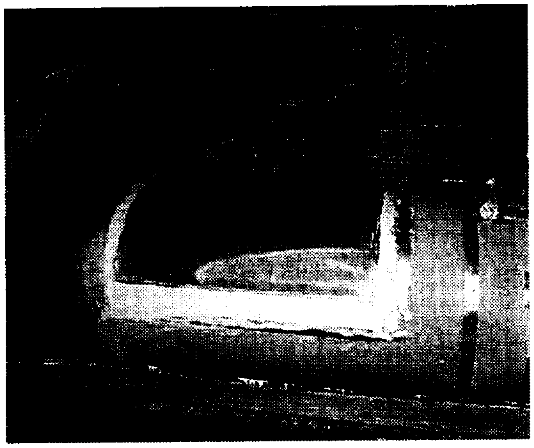


Figure 14.—Engine nacelle with Micro-Blowing Technique skin showed over 50% reduction in skin friction.

- THE HITEMP PMC SURGE DUCT HAS SIX TIMES THE DURABILITY OF THE TITANIUM SURGE DUCT.
- SURVIVED 10,000 OPERATING CYCLES WHILE THE PMC SURGE DUCT SURVIVED OVER 60,000 OPERATING CYCLES.

Surge Duct Configuration	Production Cost	Weight
Titanium Production	$2219	2.44
GR/AMB-21 Optimized	$1729	1.28

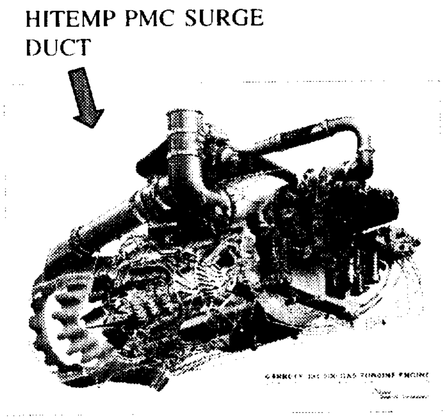


Figure 15.—Lightweight, low cost, high durability composite surge duct developed under the NASA HITEMP Program.

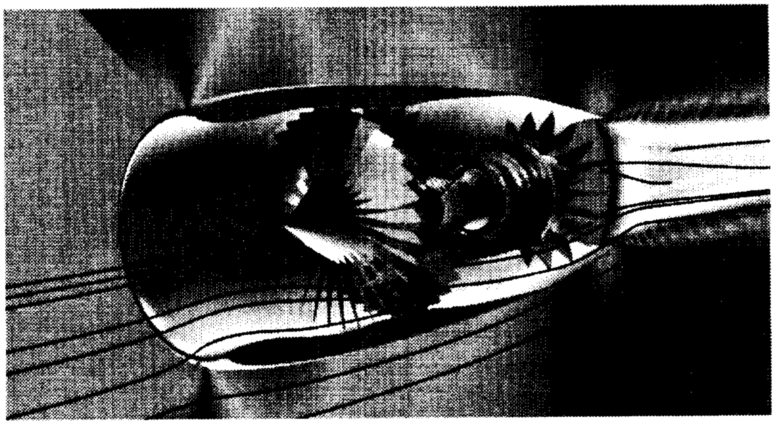


Figure 16.—The axisymmetric simulation of a full engine, showing pressure-gradient interactions, will be compared to actual engine data to verify accuracy.

TURBO-AE models flutter by combining:

- **3D Navier-Stokes (viscous) Steady & Unsteady Aerodynamics**
- **3D Finite-Element based Structural Dynamics**

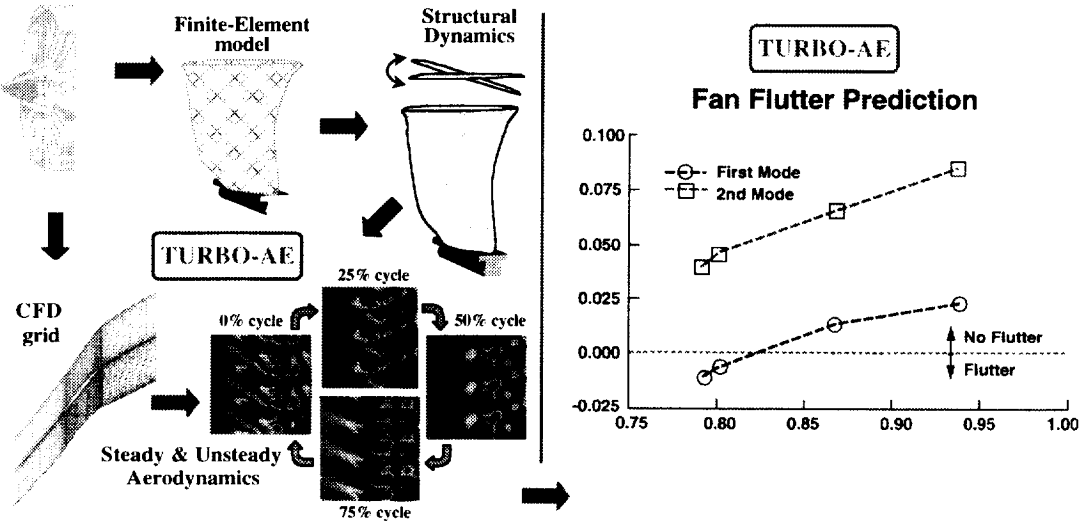


Figure 17.—Simulation of fan flutter using TURBO-AE code.

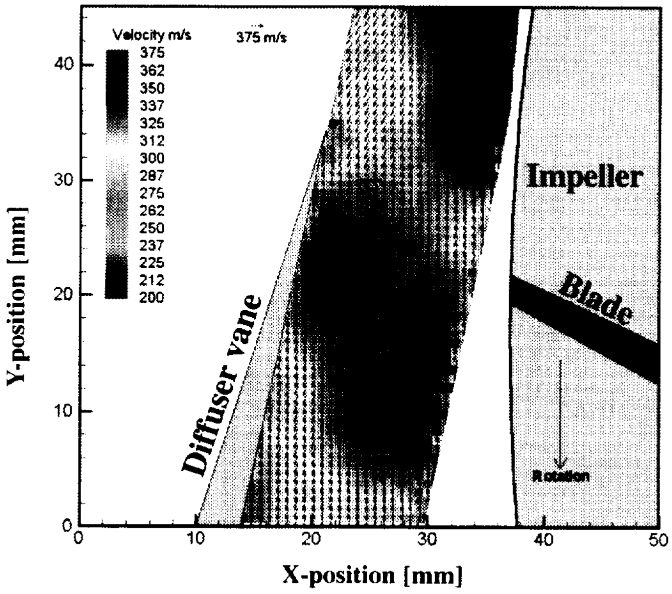
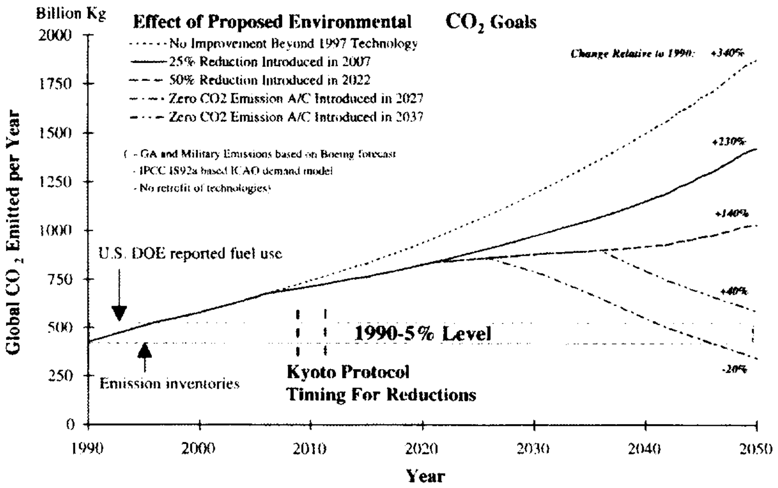


Figure 18.—Pulsed laser sheet shows instantaneous measurement of velocity field in the diffuser of a high-speed centrifugal compressor.

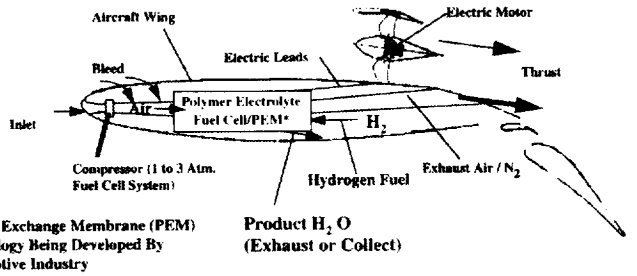
	Related Pillar Goal	CO2	NOx
Global Warming Reversal	-67%/10 yrs -80%/25 yrs	-25%/10 yrs -50%/25 yrs -100%/30-40 yrs	-67%/10 yrs -80%/25 yrs -100%/30-40 yrs
Improved Local Air Quality	-67%/10 yrs -80%/25 yrs		-67%/10 yrs -80%25 yrs -100%/30-40 yrs
Ozone Depletion Recovery	-67%/10 yrs -80%/25 yrs		-67%/10 yrs -80%/25 yrs -100%30-40 yrs

Figure 19.—ECOA emission impact metric definitions.



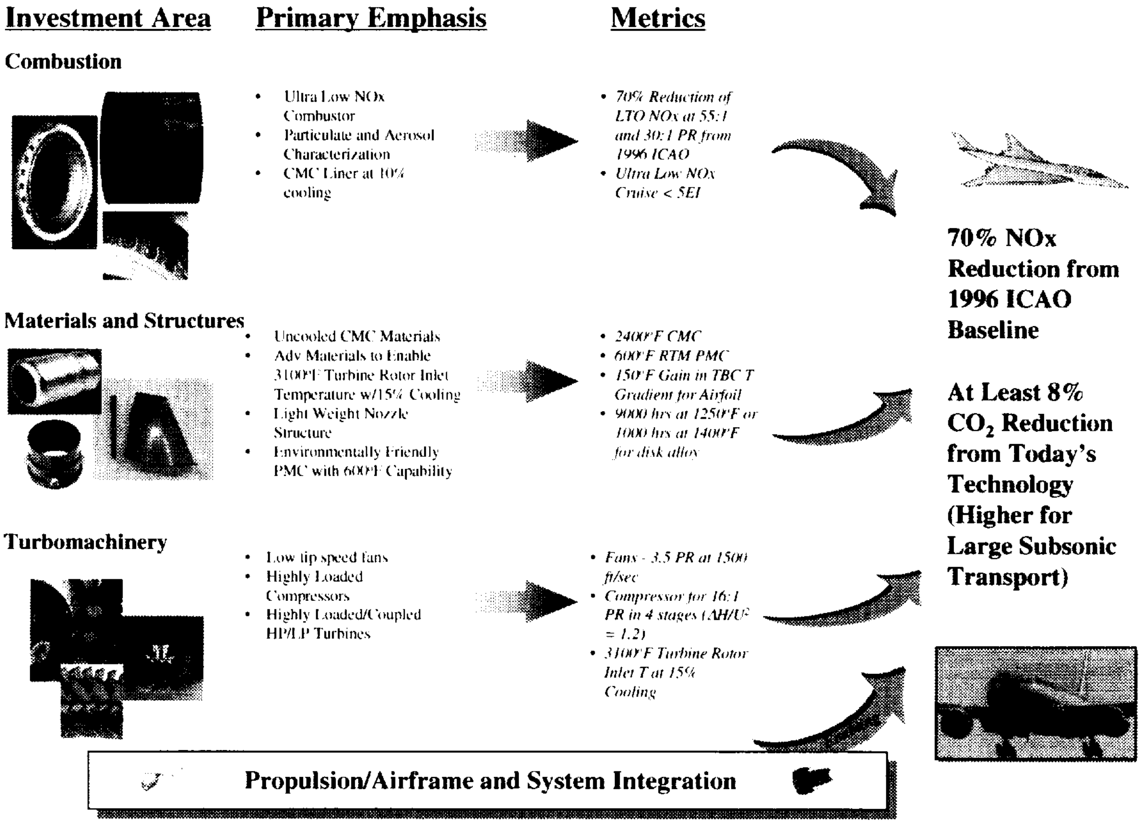
Effectiveness of Advanced Technology in Reducing Total CO$_2$ Emitted From Aircraft

Figure 20.—Aviation and the Kyoto Protocol.



PEM Fuel Cells also being applied to space transportation technology up-grades for the Space Shuttle.

Figure 21.—Fuel cell zero emissions propulsion system concept.



Investment Area | **Primary Emphasis** | **Metrics**

Combustion

- Ultra Low NOx Combustor
- Particulate and Aerosol Characterization
- CMC Liner at 10% cooling

- *70% Reduction of LTO NOx at 55:1 and 30:1 PR from 1996 ICAO*
- *Ultra Low NOx Cruise < 5EI*

Materials and Structures

- Uncooled CMC Materials
- Adv Materials to Enable 3100°F Turbine Rotor Inlet Temperature w/15% Cooling
- Light Weight Nozzle Structure
- Environmentally Friendly PMC with 600°F Capability

- *2400°F CMC*
- *600°F RTM PMC*
- *150°F Gain in TBC T Gradient for Airfoil*
- *9000 hrs at 1250°F or 1000 hrs at 1400°F for disk alloy*

Turbomachinery

- Low tip speed fans
- Highly Loaded Compressors
- Highly Loaded/Coupled HP/LP Turbines

- *Fans - 3.5 PR at 1500 ft/sec*
- *Compressor for 16:1 PR in 4 stages ($\Delta H/U^2 = 1.2$)*
- *3100°F Turbine Rotor Inlet T at 15% Cooling*

70% NOx Reduction from 1996 ICAO Baseline

At Least 8% CO_2 Reduction from Today's Technology (Higher for Large Subsonic Transport)

Propulsion/Airframe and System Integration

Figure 22.—Proposed UEET Program investment areas and metrics.

Noise Mandate

- Meet international regulations (increased stringency) and local rules
- Maintain and improve competitiveness of air transportation

Growing Noise Constraints on Air Travel

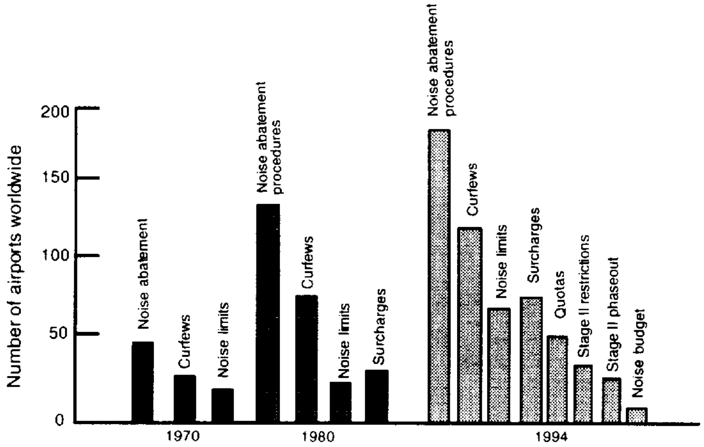


Figure 23.–Escalation in noise stringency.

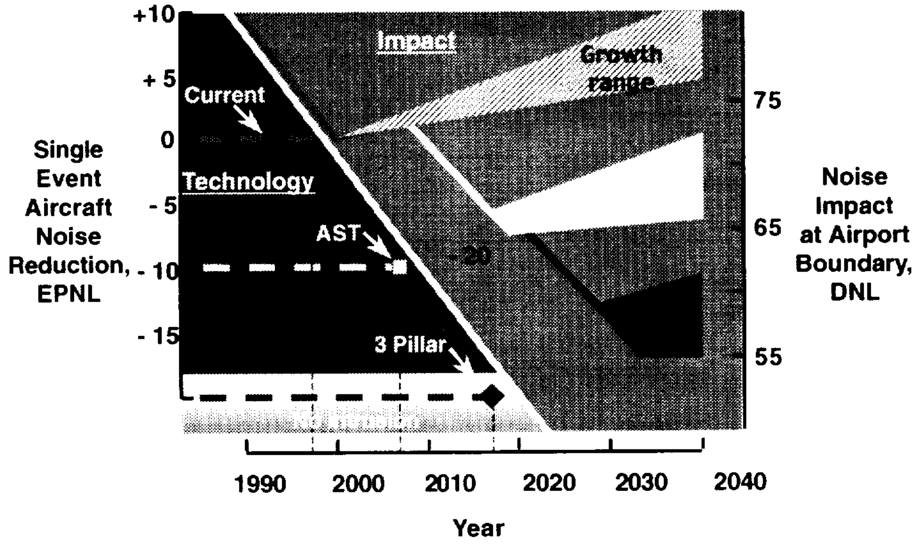


Figure 24.–Aircraft noise reduction and community impact.

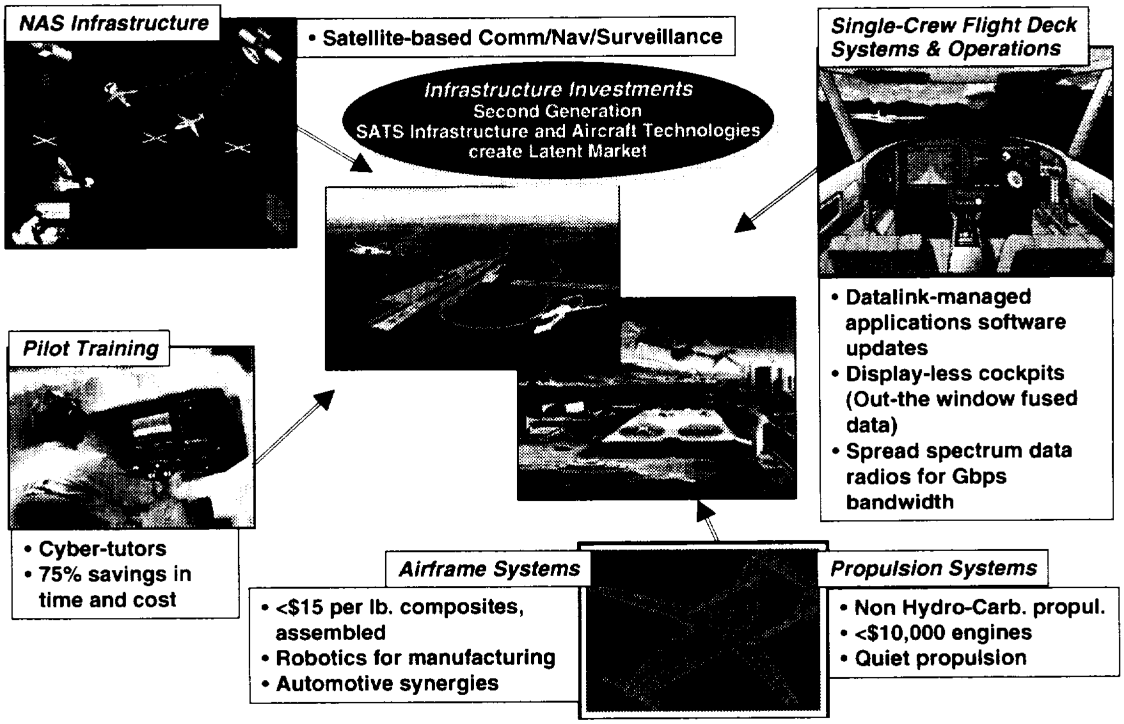


Figure 25.—Small Air Transportation System concept.

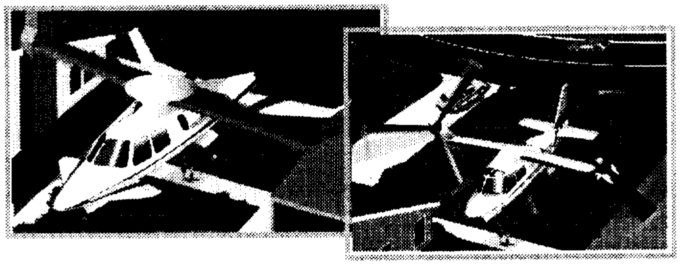


Figure 26.—VTOL aircraft concepts.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
June 1999

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Progress Toward National Aeronautics Goals

5. FUNDING NUMBERS
WU-538-17-11-00

6. AUTHOR(S)
Carol J. Russo and Arun K. Sehra

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-11707

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—1999-209193

11. SUPPLEMENTARY NOTES

Prepared for the 14th International Symposium on Air Breathing Engines sponsored by the International Society for Air Breathing Engines, Florence, Italy, September 5–10, 1999. Responsible person, Carol J. Russo, organization 2000, (216) 433-2965.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories: 07 and 03 Distribution: Nonstandard

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

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

NASA has made definitive progress towards achieving several bold U.S. goals in aeronautics related to air breathing engines. The advanced technologies developed towards these goals span applications from general aviation to large subsonic and supersonic aircraft. The proof of successful technology development is demonstrated through successful technology transfer to U.S. industry and projected fleet impact. Specific examples of progress are discussed that quantifies the achievement towards these goals. In addition, a more detailed vision for NASA aeronautics is defined and key strategic issues are explored which invite international and national debate and involvement especially in reduced environmental impact for subsonic and supersonic aircraft, dramatic new capabilities in general aviation engines, and reduced development cycle time and costs.

14. SUBJECT TERMS
Supersonic aircraft; Propulsion systems; Air breathing engines; Subsonic aircraft; Emissions; Noise; Smart controls; Design Tools

15. NUMBER OF PAGES
23

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	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102