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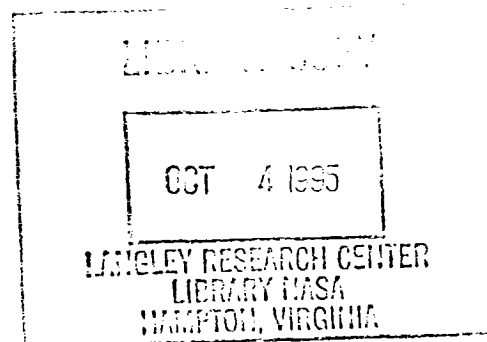
# Challenges in Aeropropulsion

Donald J. Campbell  
*Lewis Research Center*  
*Cleveland, Ohio*

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## CHALLENGES IN AEROPROPULSION

Donald J. Campbell  
National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

### SUMMARY

Aeropropulsion technologies must progress to satisfy increasingly stringent global environmental requirements with economically viable air transportation systems. In this paper, key propulsion technologies to meet future needs are identified and the associated challenges are briefly discussed. Also discussed are NASA's vision, NASA's changing role in meeting today's challenge of a shrinking research budget, and propulsion technology impacts on the environment and air transport economics. Critical aeropropulsion technology drivers are identified and their impact evaluated. The aviation industry is critical to the nation's economy, job creation, and national security. NASA's advanced aeropropulsion technology programs and their relation to the aviation industry are discussed.

### INTRODUCTION

Propulsion systems pace the development of advanced aircraft. Early propulsion system technology development and validation permit timely integration of the propulsion system into the vehicle system, thereby reducing risk and cost. Dramatic changes in the world economic and political arenas, the rise of international consortia, the trend toward more partnerships, and reduced research budgets have all created an environment within which technology development has become a high-risk undertaking crucial to remaining competitive on the world market. This situation is further complicated by global environmental awareness. The design paradigm of maximum performance has shifted to one of balanced design whereby performance, economics, the environment, and external forces and requirements all play major roles in the development of advanced aeropropulsion systems.

NASA's base research and technology (Base R&T) as well as its systems technology programs, such as Advanced Subsonic Technology (AST), High Speed Research (HSR), High Performance Computing and Communications (HPCC) and Numerical Propulsion System Simulator (NPSS), contribute significantly to developing critical aeropropulsion technologies. Lewis Research Center is committed to the continued development of key aeropropulsion technologies. This commitment is reflected in the NASA aeropropulsion budget for Lewis and is projected to be in excess of \$1.4 billion over a 7-year period (FY 1995 through FY 2001).

### BACKGROUND

The international business environment is changing rapidly. These changes are being driven by political and economic influences and a strong desire by some countries to enter the prestigious aeronautics market. This market is highly competitive and technology is the key to success. Although U.S. industry has competed well in this market, future success is not assured.

National and international consortia, partnerships, and joint production are real current trends. The competitive environment is further complicated by the fact that some foreign companies are directly or indirectly supported by their governments. New propulsion competitors are emerging in the expanding world economy. U.S. research budgets are shrinking. The drive to reduce government deficit spending and the national debt continues, the defense budget has been reduced, industry continues to down-size, and the expansion of the commercial market is slow. These factors are forcing U.S. industry to focus on the near-term needs. Joint programs tend to reduce in-house research because of limited return on investment and the fear of technology transfer to potential competitors. Fierce international competition tends to favor evolutionary technology to minimize corporate risk and capital costs. As a result, large potential gains from revolutionary technologies are no longer explored to the same extent.

Aeropropulsion system development is costly and time consuming. The multibillion dollar investment required to develop a new propulsion system in today's uncertain market is a high risk venture. NASA's aeropropulsion system technology program is being conducted to reduce development cycle, risk, and cost.

Military applications impose additional requirements and constraints on propulsion systems. The technology to detect military aircraft and take countermeasures has dictated the need for highly stealthy systems of which the aeropropulsion system is a part. Meeting logistical and economic requirements in operating from remote and rough runways have enhanced aeropropulsion system maintenance. NASA participation in military programs is undertaken to maximize transfer to civil systems.

## AEROPROPULSION CHALLENGES

Aeropropulsion technology is the pacing technology for the next century's air transportation systems. Timely technology development is a continuing process that requires long-term planning and commitment. Future transport systems must have a balance of performance, economic, and environmental attributes desired by the international air transport community.

Aeropropulsion systems must integrate contradictory requirements. Noise and emission requirements, for example, can impose serious penalties on performance, cost and/or weight. Some major technical challenges confronting the propulsion designer are

(a) Computational tools: Advances in computational capability allow more accurate designs and prediction of design concept characteristics. This presents an opportunity to overcome existing design limitations and significantly reduce engine development cycle time. Significant engine development cost savings can be realized.

(b) Active controls: Real-time intelligence in closed-loop control can optimize engine operability and performance. Advanced sensor technology combined with on-board computer capability would make this optimization feasible. Surge margin and rotating component clearance control features are two examples where maximum performance can be achieved without exceeding engine limits. Engine response to power requirements can be significantly improved using the real-time intelligence with feedback. Definition of real-time intelligence logic, sensor technology, and sensor location are the keys to success.

(c) Engine/airframe integration: Engine integration with the airframe becomes increasingly important with increasing flight speeds, particularly at supersonic and hypersonic speeds. For systems operating in a broad Mach number range, inlet and nozzle performance must be carefully traded to define an optimum system. Minimizing chemical recombination loss in a nozzle is a difficult but essential design task. Noise reduction requirements present challenging opportunities.

(d) Advanced materials: High-performance and lightweight engines require materials that withstand high temperatures in the engine operating environment. Near-term high-temperature requirements can be met with superalloys and fiber-reinforced superalloys. However, much higher temperature and strength materials, such as ceramic matrix composites and ceramics, will be needed to meet engine performance and durability requirements.

(e) Instrumentation and sensors: The existing instrumentation and sensors are limiting technologies in the development and operation of aeropropulsion systems. Advanced technology allows the realization of the full potential of engine components. High performance and/or durability can be achieved with more accurate sensors. Nonintrusive instrumentation technology such as electro-optic technology offers a quantum jump in sensor technology. Advanced instrumentation will allow an engine to be operated very close to its maximum temperature limit, thus achieving maximum power. Advanced instrumentation can be used to monitor the engine health to avoid unpredictable failures.

(f) Mechanical components: Advances in mainshafts, bearings, seals and lubrication technology operating at high speed and high temperature are critical to the advanced propulsion system. Magnetic and air bearings offer an opportunity to eliminate cooling requirements to improve performance and reduce complexity. Advanced engines require advanced design techniques to reduce component weight and improve durability.

(g) Control system: Increased onboard computer capability will allow precise control of engine functions to optimize performance. Full-authority digital electronic control (FADEC) would be integrated with the vehicle control system and the component active control system. FADEC allows the propulsion system to respond quickly to thrust requirements without exceeding any limits. Engine/vehicle operating logic development and feedback sensor technology would be the key to success.

(h) Manufacturing: An economically viable aeropropulsion system must incorporate advanced manufacturing technologies. Low-cost, low-rejection-rate, and high-durability manufacturing processes must be developed. Labor intensive processes such as machining must be minimized. Stereo lithography and solid-forming technology produce solid geometric shapes directly from digitized design data and offer potential cost reduction.

## NASA LEWIS RESEARCH CENTER VISION AND CHANGING ROLE

The NASA Lewis Research Center vision is to be the world's center of excellence in civil airbreathing propulsion in partnership with industry and academia, developing and transferring aeropropulsion technologies needed to power the next generation of U.S. aircraft and to support the global preeminence of the U.S. aviation industry. To fulfill this vision and meet the new propulsion system design challenges, Lewis has taken a collaborative approach to work with industry and academia to develop technologies needed for advanced propulsion systems. With NASA-supported and -developed technologies, industry will be able to manufacture high-performance, environmentally friendly, affordable engines and thereby promote economic growth (fig. 1).

The aviation industry is critical to the nation. The primary driving factors for this industry are contributing to the national economy, maintaining a critical transportation infrastructure, and contributing to the national defense. In addition to creating high-quality employment, the aviation industry has posted a needed positive (\$29 billion) trade balance. U.S. airlines have generated large revenues (\$60 billion) in satisfying critical transportation needs. Additionally, the aviation industry has a positive impact on the U.S. defense technology and budget.

Recognizing the importance of the aviation industry to the nation, NASA has made a renewed commitment to support this industry. This commitment is reflected in a new approach based on a NASA-industry collaboration to develop airbreathing propulsion technologies. This approach represents a shift from the traditional agency role by focusing NASA and industry efforts to collaboratively

- (a) Enable U.S. industry to employ a more timely design, development, manufacturing, and test cycle, thereby shortening the product development time
- (b) Provide highly proven technology by means of system level validation
- (c) Facilitate the introduction of new technology into the propulsion system certification process
- (d) Decrease overall development costs and increase economic competitiveness

This approach has forged a stronger technical and programmatic relationship with U.S. industry, government agencies, universities, technical societies, and international organizations. NASA is working more closely with government agencies such as the Departments of Defense and Commerce to leverage program resources to meet common technology needs. Academia is a partner in many programs to provide basic research. International partners enable technical collaboration on safety, operational issues, and R&T that transcends national boundaries.

NASA's role in the engine development cycle is significantly expanded to support technology development (fig.2). With partners, NASA's responsibility is to develop the technology to the point where industry can confidently make the additional investment necessary to integrate it in their development programs. In this partnership role, NASA provides leadership and support for key technologies, thereby reducing overall engine development cycle time and overall cost. NASA's collaborative approach includes contributing to the propulsion system validation process, an approach currently supported by industry. During the technology development phase, new materials, advanced concepts, advanced computational capabilities, and similar advancements are incorporated in NASA's Base R&T, which includes cooperative programs with industry as well as university grants. Promising new concepts pass from the base into system technology programs to demonstrate system benefits and to address component interactions.

Because aeropropulsion is a pacing technology, its needs must be addressed prior to aircraft development. To develop propulsion technology, Lewis is conducting a number of new technology programs including Advanced Subsonic Technology (AST) and High Speed Research (HSR). These are NASA-wide programs that include aircraft technology development. These programs are to demonstrate the required propulsion technologies for efficient new aircraft systems that are economically and environmentally compatible. Lewis is also developing high-speed propulsion technologies for other supersonic and hypersonic aircraft. Because of the number of new technical challenges, the High Speed Civil Transport is an exceptional example of this new approach with the cooperative successes attained to date, the size of anticipated development cycle costs, and the potential high payoff to the U.S. aeropropulsion industry.

## TECHNOLOGY PAYOFFS AND ECONOMIC IMPACT

Technology has a significant impact on the aeropropulsion system. However, technology development requires a significant commitment of resources. The technology payoffs are classified in four categories: high efficiency, low emissions, improved capability, and economic benefits. Lewis-developed and -supported technologies have resulted in advanced aeropropulsion systems, the advanced technologies for which came from such critical technology development programs as the Energy Efficient Engine (E3), the Quiet Clean Short Haul Experimental Engine (QCSEE), the Experimental Clean Combustor, and the Unducted Fan. An investment of \$2.1 billion (1995\$) from 1977 through 1990 contributed to \$113.3 billion (1995\$) direct sales (1986 to 2000).

Technology programs both maintain and enhance national core capabilities for developing future technologies and advanced systems. Skills and facilities required to execute advanced programs are national assets and must be maintained to compete in the global world economy.

Lewis technology development programs support multiple national needs from national security to environmental protection (fig. 3). Advanced aeropropulsion technologies stimulate the national competitive spirit in subsonic, supersonic, hypersonic and other critical disciplines. These technologies, in turn, have a major impact on the growth of the national economy.

## TECHNOLOGY DRIVERS AND ENABLING TECHNOLOGIES

Technology drivers are significantly influenced by external forces. Environmental awareness has reprioritized aeropropulsion design optimization. Decades ago, efficiency and performance were the key drivers in new turbofan engine design and development. Now the global aviation market is demanding lower environmental impact as well. Thus, although efficiency, reliability, and cost are still major drivers, resolving the issues of noise and emissions has greater urgency and importance. These critical technology drivers are not necessarily synergistic and must be balanced in future generations of aeropropulsion systems. Lewis has significantly contributed to this balancing of requirements and reprioritizing of technology development, delicately offsetting environmental considerations with the economic feasibility of advanced aeropropulsion systems.

Technologies required to design and develop aeropropulsion systems must address environmental and economic issues during the design phase. Enabling technologies required to satisfy environmental requirements for emissions and noise are low-NOx combustors and low-noise fans. Exhaust nozzles require careful design to balance performance and noise attenuation. Environmental constraints will continue to result in limitations of severe oxides of nitrogen (NOx). NOx limits are presented in figure 4. Proposals for future requirements indicate NOx levels to be at a constant 30 g/kN level. NASA will continue to strive to achieve these low-NOx levels through advanced combustor programs with industry.

The complex economic issue is impacted by contradictory design requirements. Primary factors that influence the economic feasibility of an aeropropulsion system are performance, operating cost, fuel cost, manufacturing, long-term durability and maintainability, affordable materials, engine weight, and component integration. Under the Lewis AST and HSR technology programs, major advances have been made to address these key technologies.

## NASA'S AEROPROPULSION PROGRAM STRUCTURE

NASA's programs are structured into two synergistic elements to effectively develop and transfer new technologies: the systems program element and the Base R&T program. The Lewis programs are vertically integrated, building on each other to effectively develop and transfer new technologies (fig. 5).

The system technology program is focused on specific vehicle classes and system validation ranging from subsonic transport to hypersonic vehicles. The overall objective of the Advanced Subsonic Technology (AST) and the High Speed Research (HSR) programs is to markedly enhance the technology base for the next-generation aircraft. The High Performance Computing and Communication (HPCC) program is developing the Teraflop computing capabilities needed to analyze increasingly complex aircraft and engine systems. The Numerical Propulsion System Simulation (NPSS) program is intended to simulate complete engine behavior, reducing the design, test, and redesign iteration currently used to meet design goals. The total planned budget for these four aeropropulsion programs is in excess of \$1.4 billion from FY 1995 through FY 2001.

The Base R&T program provides the fundamental technologies and enables the initiation of new system technology programs. These technologies can also be used in existing systems. Some of the key fundamental technologies developed under the Base R&T are materials, structures, computational tools, instrumentation, sensors, engine components, and controls. The Base R&T for Lewis is currently about \$74 million per year.

The two synergistic elements provide demonstrated technologies ready for integration by industry to aeropropulsion system development with reduced risk and cost.

## MAJOR PROPULSION TECHNOLOGY PROGRAMS

Lewis Research Center has initiated technology programs to enhance the technology of aeropropulsion systems. The current programs include HSR, AST, NPSS/HPCC, and the Base research and technology program. These technology programs are developing enabling technologies that range from emission reduction to advanced materials for very high-temperature operating conditions. A summary of these programs follows.

### High Speed Research (HSR)

Ongoing NASA-funded studies continue to indicate that an opportunity exists for a second-generation supersonic transport to become a key part of the 21st century international air transportation system. The large potential market for an HSCT is shown in figure 6. However, significant advances in airframe and propulsion technologies over the levels currently available will be required for an HSCT to become a reality. These technologies must contribute to an aircraft design that is both environmentally compatible and economically viable. The environmental barrier issues facing the HSCT are depletion of the Earth's ozone layer, resulting from HSCT exhaust products, and airport noise. The economic viability will require superior performance with low weights, long-term durability in extreme operating conditions, and low manufacturing costs for the required new materials and components.

Recognizing the large potential market, NASA initiated the HSR program to address these barrier issues. The vision of the program is to establish the technology foundation by the year 2001 to support the U.S. transport industry's decision for a 2006 production of an environmentally acceptable, economically viable aircraft with notional design features of a 300-passenger capacity, 5000-n mi range, and a Mach-2.4 cruise speed. The three elements of the program are airframe, systems integration, and propulsion. The propulsion element receives the largest share of the budget because it must overcome a number of barrier issues. Technologies for new low-NO<sub>x</sub> combustors are being developed to reduce ozone depletion. Assessments of the effects of HSCT exhaust on the atmosphere have been made using state-of-the-art two- and three-dimensional atmospheric modeling codes. Recent results from these models have shown steady-state ozone depletion to be substantially less than 1 percent for an HSCT fleet that meets the HSR goal emissions index (EI) of 5 g NO<sub>x</sub>/kg fuel. Flame tube experiments of new HSR combustion concepts have produced an EI in the range of 2 to 10, giving a strong indication that the EI goal is achievable. These concepts have moved into the more substantial combustor sector tests, and early test results have produced EI's surpassing the interim goal of no greater than 20 g NO<sub>x</sub>/kg fuel. These designs will be further refined and tested before a final combustor design selection is made and a full annular combustor is tested to verify the technologies required for achievement of the EI goal of 5 g NO<sub>x</sub>/kN. The other environmental issue, airport noise, also impacts primarily the propulsion system. Reducing engine noise becomes essentially a task of reducing nozzle jet velocity to approximately 1400 ft/sec to meet a noise goal of FAR 36 stage III, with a margin. Achieving this goal is a tradeoff between cycle selection, nozzle noise suppression, and engine sizing. The selected current HSR engine configuration is a mixed-flow turbofan of moderate bypass ratio to significantly reduce nozzle jet velocity. Jet velocity will be reduced with a mixer/ejector nozzle to meet the noise reduction goals. However, tradeoff studies at the system level will continue to ensure the selection of the optimum cycle/nozzle combination that meets program goals.

Another barrier issue facing the HSCT is economic viability, which will require engines with a superior performance and weight that result in an aircraft of reasonable size. The projected HSR vehicle and the current Concorde are compared in figure 8. Advanced, high-temperature engine materials will contribute to the HSCT environmental and economic success. The primary materials being developed are ceramic matrix composites for the combustor liner, intermetallic/metal matrix composites for the nozzle, lightweight composites for fan containment, and long-life materials for compressor and turbine disks and turbine blades. Other materials required for the

propulsion system are being developed in other Department of Defense (DOD) and NASA programs. In addition to good performance and light weight, long-term durability becomes a design issue because the duty cycle of an HSCT engine is much more demanding than that of current subsonic transport engines. Long life for critical components such as compressors, turbines, and nozzles exposed to long-duration, high-temperature environments will have to be demonstrated. The development of new materials and new component designs is not sufficient; manufacturing cost will have to be reduced to ensure the future success of an HSCT.

The current HSR program will demonstrate the aerodynamic and acoustic performance of the critical propulsion components through isolated, large-scale (approximately 1/3 full scale) component tests. These tests will reduce the development risks associated with an HSCT, enabling the U.S. manufacturers to proceed toward an informed product launch decision as early as 2001.

### Advanced Subsonic Technology (AST)

The AST program is a NASA-U.S. industry-FAA partnership for developing high-payoff technologies to enable a safe, highly productive global air transportation system. This system will include a new generation of environmentally compatible, economical subsonic aircraft. The AST elements at NASA Lewis Research Center include propulsion, fly-by-light/power-by-wire, engine noise reduction, and short haul (civil tiltrotor and general aviation) propulsion technologies.

Propulsion.—NASA Lewis and the U.S. aircraft engine manufacturers are developing technology to reduce emissions of oxides of nitrogen (NO<sub>x</sub>) by 70 percent, reduce direct operating cost (DOC) by 3 to 10 percent, and improve fuel efficiency by 8 percent. These technologies will be incorporated in future (2005 entry-into-service) engines and transitioned into derivatives and enhancements of in-service engines. Future engines range from large (20 000 to 100 000-lb thrust) for commercial transports of 700 or more to small (5000 to 20 000-lb thrust) for regional transports of 50 passengers.

Studies recently completed by the U.S. aircraft engine manufacturers revealed that these engines will process about twice as much airflow, with bypass ratios up to 20:1, operate at higher temperatures and pressures to improve efficiency, at peak temperatures of 3000 °F and pressure ratios up to 60:1, and burn fuel in low-emission combustors. These engines will depend on lightweight composites and geared engine systems to enable very high bypass ratios, will use improved metallic disk, blade, and case materials, and incorporate improved turbomachinery. Validated turbomachinery aerodynamic and aeroelastic design codes are being developed to reduce development testing and cost and the time to bring an engine to market. Low-emission combustor studies have identified promising concepts and barrier technologies. Screening tests are underway to address the technology barriers and to facilitate the development of low-emission combustors. Testing will be conducted in a state-of-the-art, high-pressure, high-temperature combustor facility at Lewis.

Fly-by-light/power-by-wire technology (FBL/PBW).—The goal of this element is to provide lightweight, highly reliable, highly electromagnetically immune fiber-optic-based control systems and all-electric secondary power systems. These technologies will lower acquisition and direct operating costs, reduce weight, and increase performance and reliability (fig. 8). The FBL plans include an airplane control system design and the detailed design, fabrication, and flight demonstration of an FBL-controlled, aileron electrical actuator (EA). The PBW plans include detailed design, fabrication, and ground test of an airplane power management and distribution (PMAD) system and starter-generator, and the design, fabrication, and flight demonstration of an aileron EA integrated with the FBL system. Flight tests are to be performed on NASA's 757 TSRV-II aircraft in 1999. Additional flight tests of an FBL/hydraulic control system are scheduled for 1996 on NASA's F-18 aircraft. To date, the FBL system design has been completed and detailed design is underway. The F-18 FBL/hydraulic hardware will soon be installed and flight tests will commence. The PMAD architecture has been down-selected from 10 concepts, the design has been completed, and the detailed design is underway. The detailed designs of the starter-generator and the flight EA are also underway.

Noise Reduction.—The goal of this element is to reduce the engine noise 6 dB by the year 2000 (relative to 1992 technology). Three areas of engine noise reduction are being investigated: jet noise, advanced low-noise fan designs, and active control of fan noise. Experimental and analytical work is being performed in all three areas. Jet noise tests were conducted in collaboration with industry in the NASA Lewis Aeroacoustic Propulsion Laboratory (APL) and at industry sites. Fan testing was conducted on a research model in the Lewis 9- by 15-Foot Low-Speed Wind Tunnel where aeroacoustic, aerodynamic, and structural data were obtained. A diagnostic fan test was

performed to identify dominant fan broadband noise sources. A test was completed with engines in the Lewis APL to demonstrate an active noise control (ANC) concept using a large low-speed fan. In addition to experimental work, several analyses were developed with industry to predict jet and fan noise and were applied to many of the test configurations for code validation. This effort includes new or improved fan tone prediction, fan broadband, and jet noise prediction codes.

Short Haul - Civil Tiltrotor.— A civil tiltrotor aircraft is viable for air transport that provides relief when traffic is congested. Technology developments in noise, terminal area operations, safety, weight reduction, and reliability remain barriers to acceptance and implementation of the tiltrotor concept. Tiltrotor research at Lewis centers on improved system safety, specifically tiltrotor operation in the emergency contingency power (one-engine-inoperative or OEI) condition. Three industry efforts are currently underway to evaluate the full range of concepts for engine power augmentation in the event of an OEI condition. By the end of FY97, preliminary designs of the most promising contingency power concepts will be prepared and ranked, and at least one of the preliminary designs will be selected as a candidate for detailed design. Current plans include an engine system technology demonstrator in FY 2000; this demonstrator will be used to validate OEI technology and demonstrate the selected system's ability to meet the OEI safety requirement at minimum vehicle cost.

Short Haul - General Aviation.— Lewis is working with the general aviation (GA) industry to provide technology for improved safety and performance of general aviation aircraft. To make GA easier to use, Lewis efforts focus on advanced propulsion sensors and controls for simplified controls of intermittent combustion engines and aircraft. Lewis icing expertise is being applied to aircraft ice avoidance and deicing methods and sensors. Lewis also has three study contracts to examine the application of existing military and automotive small gas turbine technology to the GA market. These studies include an evaluation of critical GA noise, emissions, and performance issues. The Lewis general aviation propulsion programs are defined jointly with industry and are executed through methods appropriate for the industry it serves.

#### Advanced Computational System Programs (NPSS/HPCC)

The primary objective of Numerical Propulsion System Simulation (NPSS) is to develop the technologies necessary to perform large, computationally intensive system and subsystem simulations of aircraft engines in a cost-effective and timely manner. NPSS, referred to as the "Numerical Test Cell," is being developed in close coordination with the aeropropulsion industry to assure that the software will meet its needs. Computer simulation of aeropropulsion systems is primarily limited to modeling single components with codes of a single discipline, such as the structural or aerodynamic analysis of inlets, compressors, combustors, nozzles, or other elements of the system. Lewis has traditionally been a major participant in developing codes for the aeropropulsion industry. With greater computing capability expected in the future, the current strategy is to develop the capability to computationally model the complete engine and capture the real physical interactions that take place between the components in the engine (fig. 9). The effects of component interaction on engine performance have been quantified in full-scale tests. Such tests have been time consuming and costly to perform. Simulating tests "numerically" early in the design process promises to substantially reduce the time and cost of developing and certifying engines and thereby help the U.S. aeropropulsion industry maintain its preeminence in the world market. Estimates indicate that over 18 months and approximately \$300 million could be saved in the development and certification of a new engine.

The financial support for the NPSS project comes from the High Performance Computing and Communication (HPCC) Program and the Base R&T. HPCC is a national program with the goal of significantly advancing the computing capabilities in the U.S. The key elements of advanced computational systems are summarized in the following:

High performance computing.— Integrating complex applications with advanced computational hardware and system software will reduce the time required to perform simulations. The current Lewis focus is to develop and implement computing and communications technologies that permit large simulations to be executed simultaneously (in parallel) on several processors. To make effective use of the computing resources, the processors may reside in supercomputers or desktop workstations or multiprocessor systems. The Lewis Advanced Cluster Environment (LACE) is a group of distributed, 32 networked IBM RS/6000 desktop engineering workstations. LACE is used as the primary testbed for developing NPSS parallel application codes and system software to take advantage of the large number of workstations in use in the aerospace industry.

Axisymmetric engine simulation (ENG10).—The ENG10 code is to provide a high-fidelity flow model in an aircraft gas turbine engine (fig. 10). It provides a two-dimensional flow field that captures engine component interaction effects on system performance.

Combustion simulation (CORSAIR).—CORSAIR enables the analysis of a full combustor from compressor exit to turbine inlet. It reduces design cycle time by executing an unstructured mesh analysis on distributed desktop workstations. It has been recently selected as the basis of the flow solver for the National Combustor Code for further development by a NASA-DOD-DOE-U.S. industry partnership.

Coupled aerodynamic-thermal-structures (CATS).—CATS is to be a multidisciplinary simulation process to improve compression system designs. Turbomachinery compressor performance, including stall, is strongly influenced by a combination of aerodynamic, thermal, and structural effects. The interactions among these disciplines have been neglected because of a limited ability to exchange data among discipline codes in a timely and efficient manner. CATS is to result in data management and data exchange among turbomachinery discipline codes, such as CFD and finite-element structural and thermal analyses, and the component geometry on CAD/CAM systems. The goal is to reduce multidisciplinary analysis time by 50 percent and to improve stall margin prediction by 10 percent.

Visual computing environment (VCE).—VCE allows coupling analysis codes of various engineering disciplines such as CFD, structural, and thermal, with the capability of performing simulations with different dimensionality or fidelity, empirical performance-map-based modules linked with full three-dimensional transient CFD simulations, for example. VCE will permit the coupling of multicomponent analysis codes. The modules in VCE are typically distributed across several computer processors, allowing VCE to take advantage of inherent coarse-grained parallelism.

Portable extensible viewer (PEV).—PEV Team is a viewer for nonuniform rational b-spline (NURBS)-based geometry capable of operating on desktop computers from a variety of different vendors, permitting the use of computing systems of choice by the aerospace industry.

Workspace simulation manager.—The NPSS workspace is a standard graphical user interface (GUI) windowing system used for launching and administering simulations, a “Windows for engines,” serving as the top-level view of the NPSS environment that establishes a consistent platform.

Advanced communications technology.—A series of numerical experiments utilizing the Advanced Communications Technology Satellite (ACTS) are being conducted to develop a high-speed inlet control system using the NPSS. The engine inlet simulator is executed on the Lewis Cray YMP supercomputer but is controlled by Boeing Corporation in Seattle, Washington. Flow visualization information is transported via the ACTS to the remote site for quasi-real-time display on high-performance, three-dimensional graphics workstations. The experimental ACTS satellite network allows remote access of NASA’s distributed engine inlet simulation application to aerospace manufacturers.

## Base Research and Technology

The Base R&T program consists of multiple program elements that are focused on advancing the fundamental understanding in aeropropulsion and span multiple vehicle classes. These elements include improvements in propulsion components in both the core and low-pressure systems as well as in materials and structures, instrumentation and controls, and computational fluid dynamics. Universities are important partners in the Base R&T program. The following examples illustrate these partnerships.

HITEMP.—This program is a very productive partnership including NASA Lewis, universities, industry, and other government agencies. Figure 11 shows the objectives of this program and the breadth of the teaming. Several new materials have already been produced and have been successfully transferred, by additional industry development, to several modern propulsion systems, dramatically reducing weight and cost. The methodologies to design actual components and to predict their life have also been developed and transferred.

Airbreathing propulsion for hypersonic flight.—The objective of this element of the Lewis aeropropulsion program is to develop and demonstrate technologies for airbreathing hypersonic flight for global access and space access. Flight-validated, all-speed, integrated airbreathing propulsion systems, used from takeoff to the final flight Mach number, will be provided by means of ground testbeds and experimental flight.

Requirements are defined by means of mission and/or system analysis of potential applications. Multidisciplinary optimization of the final system is conducted to obtain the final design. The elements integrated

into the final system include the following: turbine engines, thermal management systems, heat exchangers, ejectors; inlets, diffusers, combustors, fuel systems, nozzles, and rockets. Enabling component and system technologies are developed and demonstrated in ground test facilities, such as the Hypersonic Tunnel Facility (HTF) and the Propulsion Systems Laboratory (PSL). Flight experimentation, validation, and demonstration are conducted to reduce the risk of airbreathing hypersonic flight.

Challenges exist in defining the analytical, ground, and flight program elements, content, and coupling. Challenges exist technically in defining the propulsion system for a given mission or application and in optimizing the total system with accepted criteria. Technical challenges include developing the highly integrated systems defined as above. These challenges are compounded by the lack of complete ground test capability (scale, Mach number, degree of integration, and the adequacy of the physics of simulation), CFD with real gas effects, and affordable flight test capability with its real constraints of limited instrumentation, limited test condition variability, and limited configuration changes.

The aeropropulsion program is a representative participant in the impending NASA flight demonstration program. A global access x-plane family is expected to be the focus of a portion of that program. Preliminary candidate airbreathing propulsion systems have been identified, including turbine-based, combined-cycle (TBCC) and rocket-based, combined-cycle (RBCC) systems. Long-lead planning is being conducted. Facility preparation is in progress; steady flow in direct-connect and free-jet configurations can be tested to Mach 7, pulsed flow to Mach 14+. A scramjet will be flight tested by Russia's CIAM for NASA to Mach 6.5 to provide limited data for ground-flight-analysis correlation and to demonstrate flight test techniques.

A test program is underway to demonstrate the rocket-based, combined-cycle concept for application to high-speed cruise missions and accelerator missions such as space access. Analytical (cycle code) predictions show that this engine system has the potential to maximize the overall ISP of the propulsion system for these missions. The focus of this program is a free-jet test series of a RBCC engine at Mach 5 to 7 in the HTF. A substantial amount of work has been accomplished in support of this program. The engine design has been completed. The HTF facility is fully operational. All new support systems have been defined and designed. A parametric subscale inlet model (40 percent scale) of this RBCC engine design was tested in the NASA Lewis 1- by 1- Foot Supersonic Wind Tunnel at Mach- 5 to -7 conditions. This test contributed to defining the final RBCC engine geometry and established the operability and performance of this geometry. A direct-connect combustor test is underway to verify the operability and performance of the RBCC combustor and to optimize the combustor geometry and fuel staging scheme for the HTF test conditions. A data set has been obtained at Mach 6, and additional tests at Mach 7 are planned.

## FUTURE PLANS

NASA is already planning future activities to continue to advance and validate aeropropulsion technologies. We will continue to work with industry, academia, and other government agencies to develop future programs. It is anticipated that high speed research and advanced subsonic propulsion systems will continue to need focused system development in key areas. Lewis proposes to integrate all critical technologies in a demonstrator engine to verify system performance, acoustics, emissions, and durability as a follow-on for the HSR program. Planning for technologies beyond the next generation of subsonic transport systems is also being considered. After completion of the NPSS software that will perform a high-fidelity multidisciplinary analysis of the complete gas turbine engine, plans are to integrate it with airframe analysis and design systems. This combined capability will enable designers to evaluate the three-dimensional multidisciplinary interaction effects between the propulsion system and the airframe at all operating conditions. Integrated propulsion system performance must be validated with the direct-connect and free-jet test data. Viable systems will be flight tested. Design methodologies will be available for the implementation of airbreathing hypersonic flight.

## CONCLUSIONS

The aviation industry is critical to the national economy. Aeropropulsion technologies are essential to satisfying the global environmental requirements attendant to economically viable transport systems. The aeropropulsion system has been recognized as the pacing technology for developing advanced aircraft. Technology development and timely implementation into future systems is a continuing process that requires a detailed long-term planning and commitment as well as a balanced approach between environmental considerations and economic

feasibility. NASA Lewis will continue to strengthen its programs and partnerships to develop and transfer key aeropropulsion technologies addressing national and international priorities. These collaborative programs will play an increasingly important role in ensuring U.S. leadership in aeropropulsion and advancements in safety and fundamental research. NASA Lewis Research Center has demonstrated technology advancement in critical technologies areas and is ready to meet the challenges of the future.

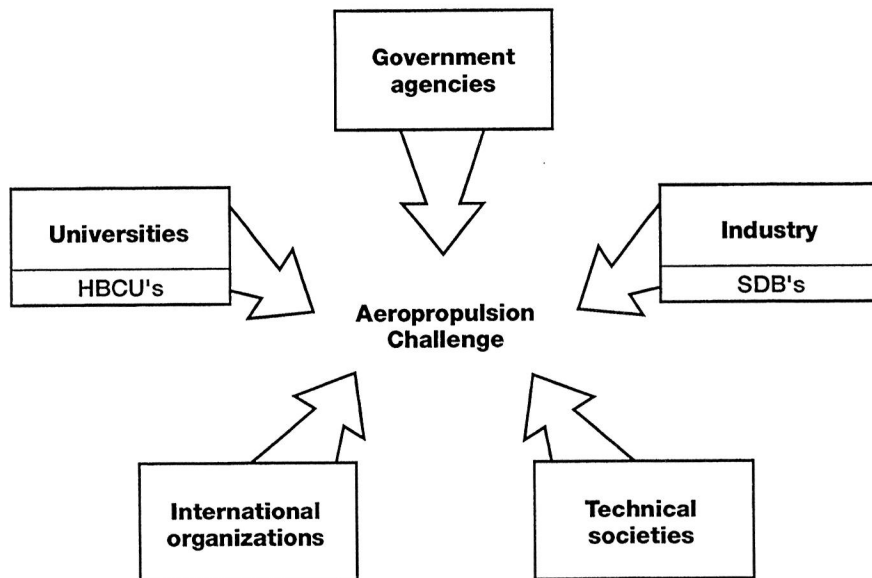


Figure 1.—NASA Lewis Research Center's growing aer propulsion technology partnership.

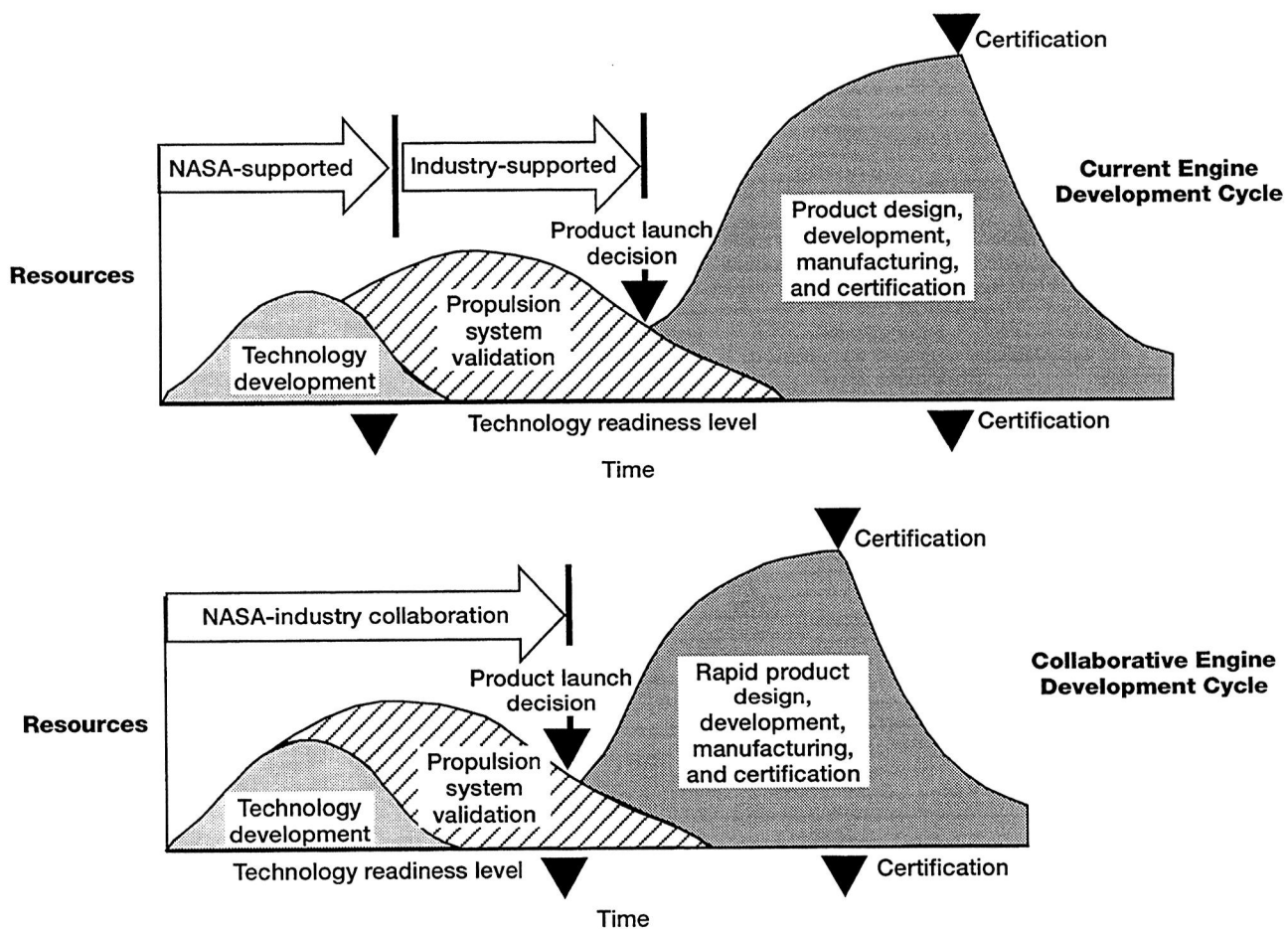


Figure 2.—Engine development cycle.

| Lewis roles/missions:<br>aerostrategic thrusts | Fundamental<br>science | National<br>security | National<br>competitiveness<br>and economic<br>growth | Environmental<br>protection | Aerospace<br>experiments<br>and space<br>R&D | Community<br>and<br>education |
|------------------------------------------------|------------------------|----------------------|-------------------------------------------------------|-----------------------------|----------------------------------------------|-------------------------------|
| Subsonic propulsion                            |                        |                      | X                                                     | X                           | X                                            | X                             |
| High-speed propulsion                          |                        |                      | X                                                     | X                           | X                                            | X                             |
| High-performance propulsion                    |                        | X                    | X                                                     |                             | X                                            | X                             |
| Hypersonic propulsion                          |                        | X                    | X                                                     |                             | X                                            | X                             |
| Critical disciplines                           | X                      | X                    | X                                                     | X                           | X                                            | X                             |
| Facilities                                     | X                      | X                    | X                                                     | X                           | X                                            |                               |

Figure 3.—Multiple national needs supported by Lewis aeropropulsion programs.

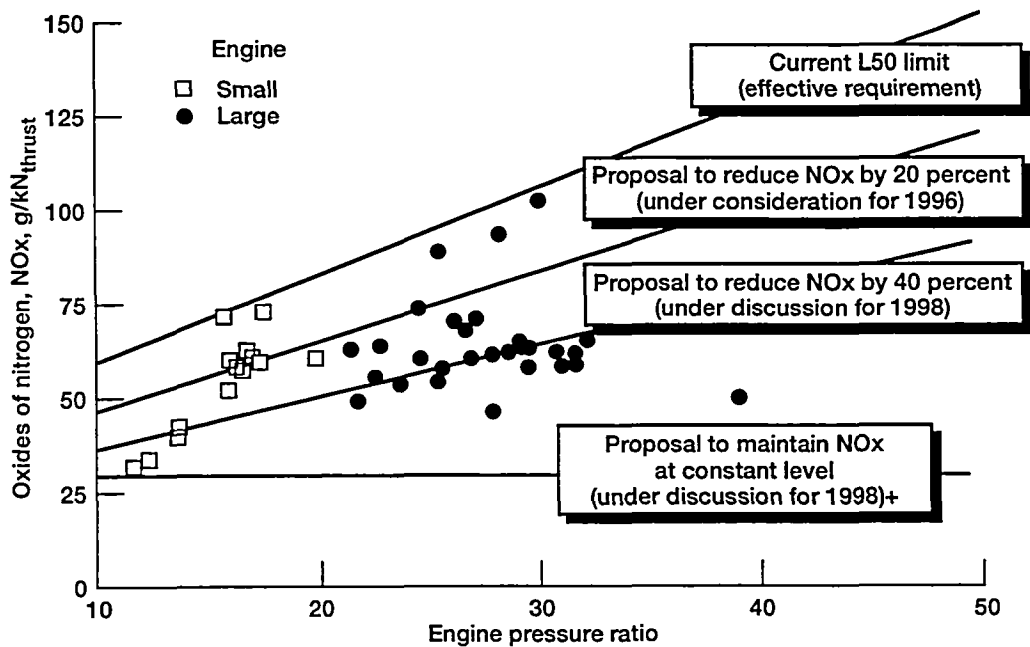


Figure 4.—Subsonic engine emissions (ICAO projections).

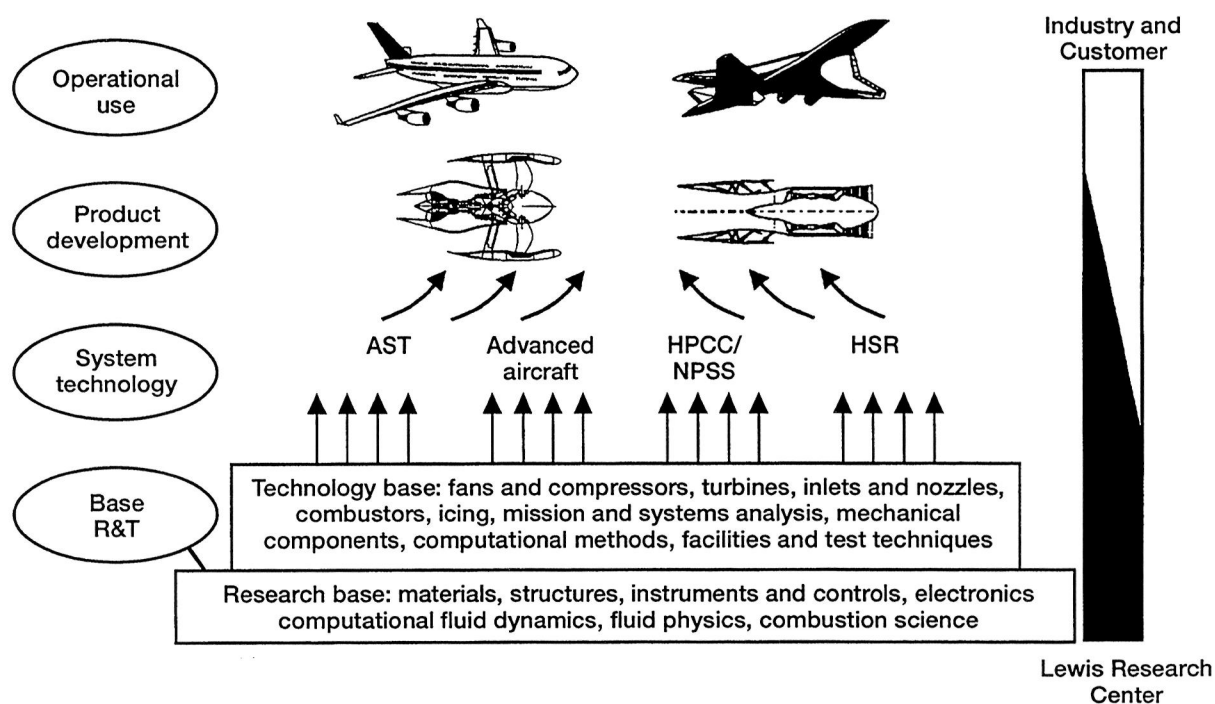


Figure 5.—Vertical integration of Lewis aer propulsion program.

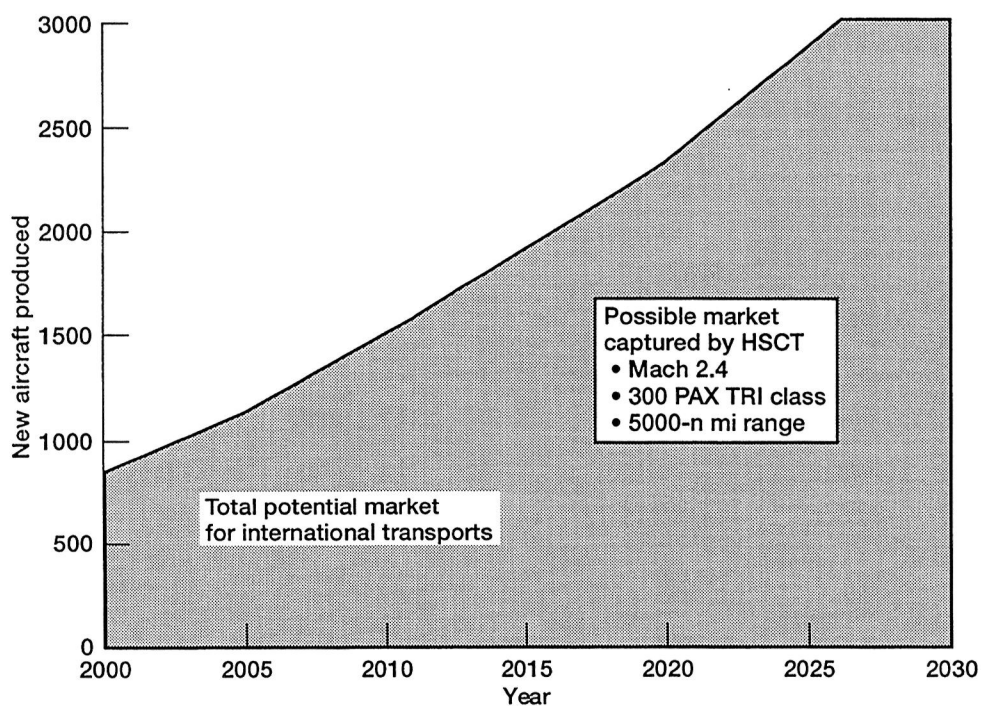
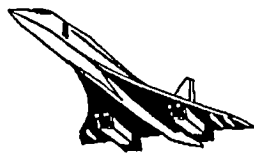
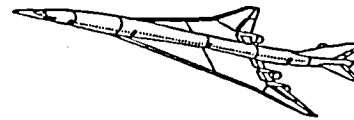


Figure 6.—High Speed Civil Transport (HSCT) market estimate (from Boeing).



**Concorde**



**HSCT Goals**

| North Atlantic | Market                               | Atlantic and Pacific |
|----------------|--------------------------------------|----------------------|
| 1976           | Entry-into-service year              | 2005                 |
| 2.0            | Speed (Mach number)                  | 2.4                  |
| 3000           | Range (n mi)                         | 5000 to 6500         |
| 100            | Payload (passengers)                 | 250 to 300           |
| 400 000        | Takeoff gross weight (lb)            | 700 000              |
| 87             | Required revenue (¢/rpm)             | 10                   |
| Premium        | Fare levels                          | Standard             |
| Exempt         | Community noise standard             | FAR 36 stage III     |
| 75             | Noise footprint (mile <sup>2</sup> ) | 5                    |
| 20             | Emissions index (gm/kg fuel)         | 5                    |

Figure 7.—High Speed Civil Transport comparative perspective.

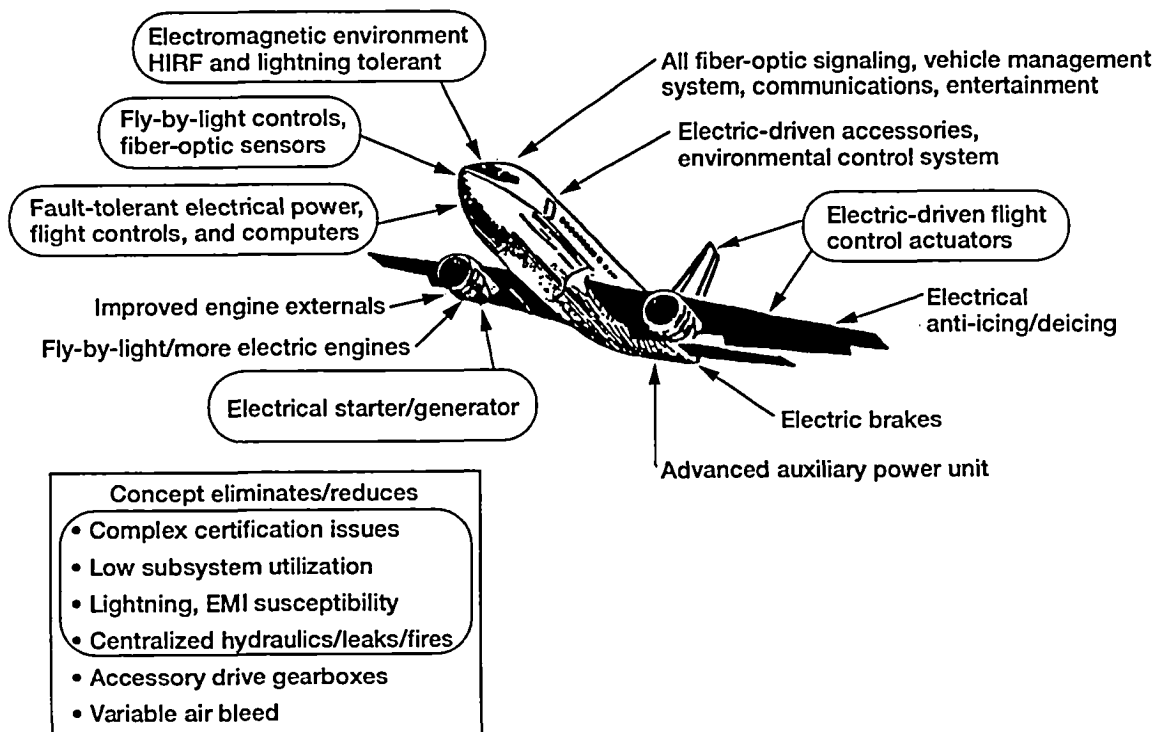


Figure 8.—Fly-by-light/power-by-wire subsonic transport aircraft. Increases reliability; reduces costs, weight, and fuel consumption.

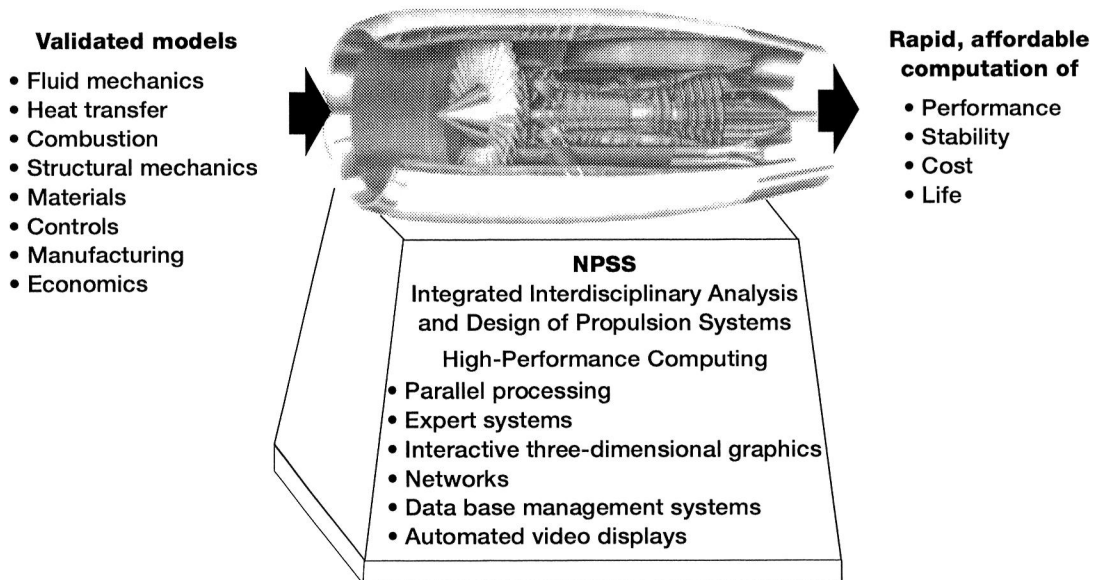


Figure 9.—Numerical Propulsion System Simulation (NPSS), a numerical test cell for aerospace propulsion systems.

### Objective

Develop the capability to computationally evaluate the interactions between components and full engine.

### Approach

Model components in the engine simulation as source terms computed by the design code. Engine-component interactions take place through boundary conditions.

### Impact

Reduce engine development time and cost by enabling the evaluation of component designs including the full engine interactions early in the design cycle.

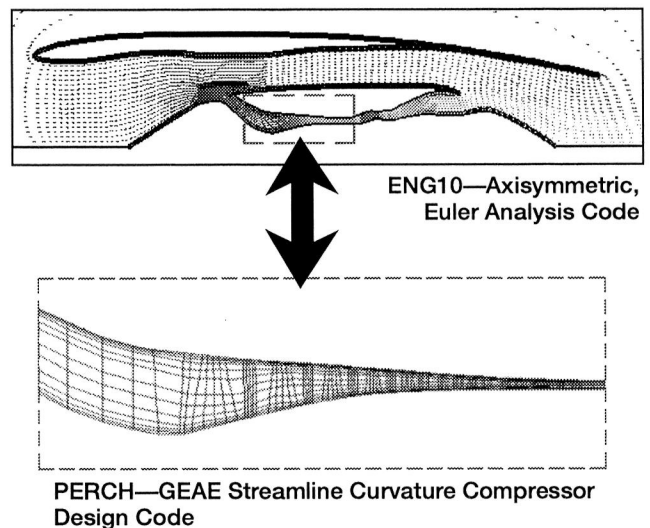


Figure 10.—NPSS demonstrates axisymmetric engine simulation coupled to compressor design code.

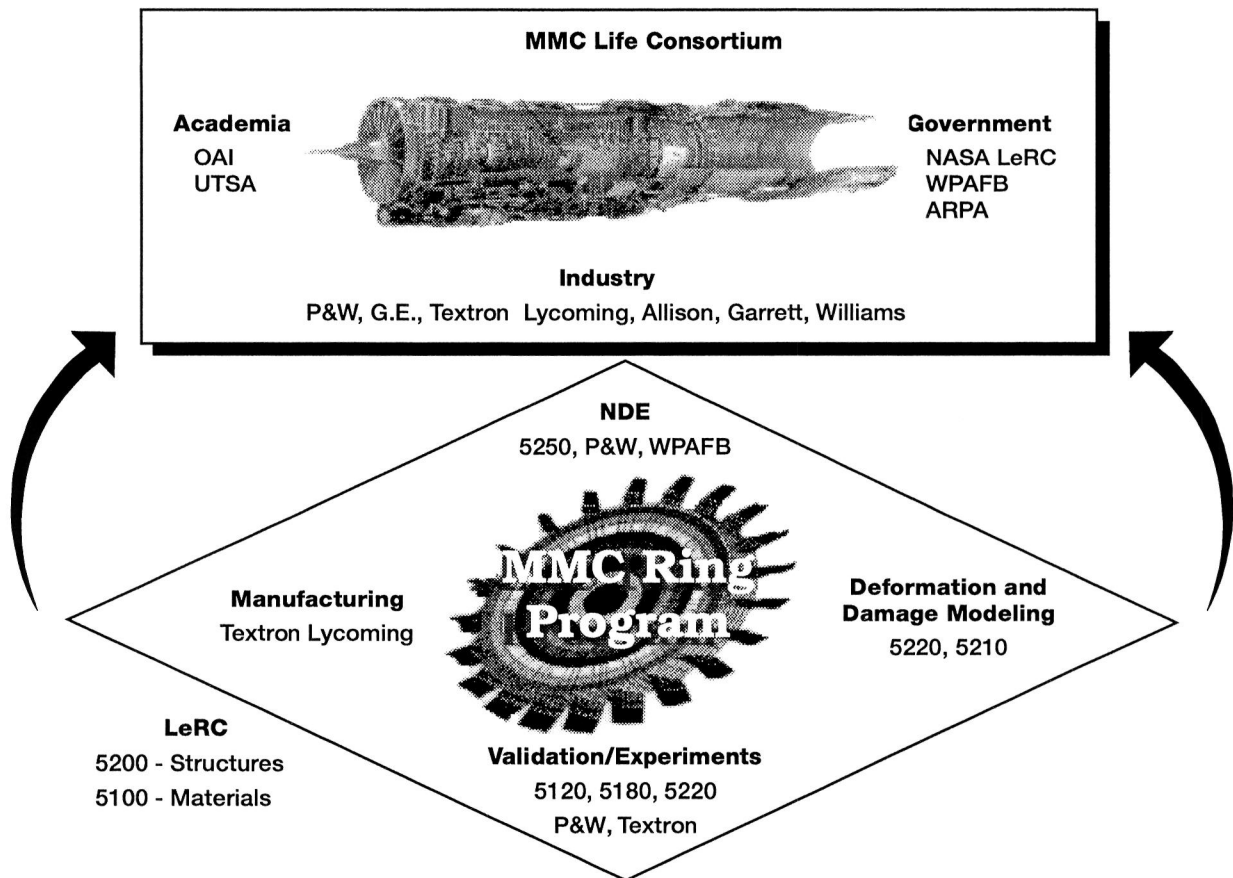


Figure 11.—Base R&T program partnership.

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