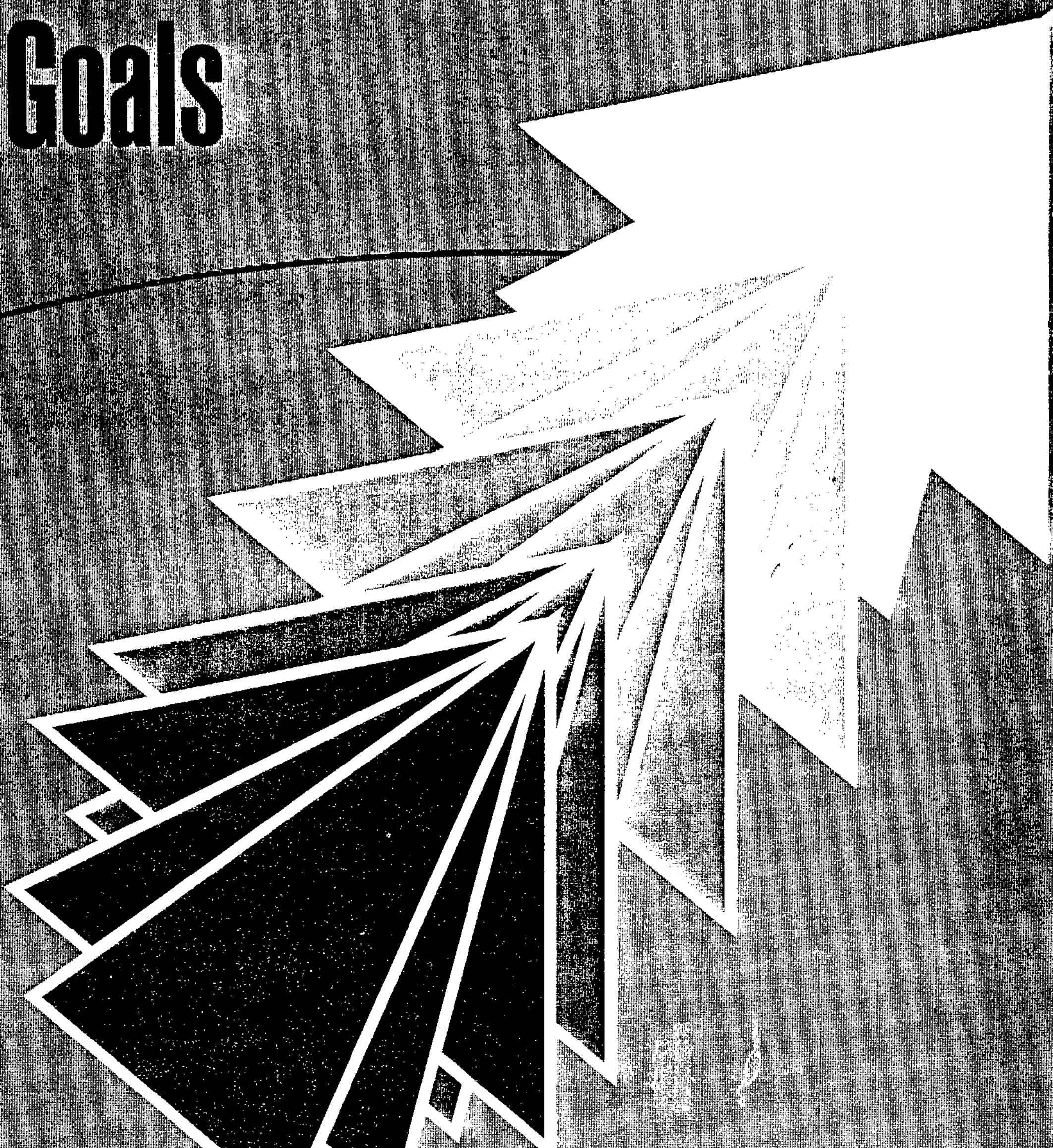
MAINTAINING U.S. LEADERSHIP IN AERONAUTICS

Breakthrough Technologies to Meet Future Air and Space Transportation Needs and Goals



NATIONAL RESEARCH COUNCIL

Maintaining U.S. Leadership in Aeronautics

Breakthrough Technologies to Meet Future Air and Space Transportation Needs and Goals

Committee to Identify Potential Breakthrough Technologies and Assess Long-Term R&D Goals in Aeronautics and Space Transportation Technology

Aeronautics and Space Engineering Board

Commission on Engineering and Technical Systems

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1998

This study was supported by Contract No. NASW-4938 between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for the project.

International Standard Book Number: 0-309-06226-8

Available in limited supply from: Aeronautics and Space Engineering Board, HA 292, 2101 Constitution Avenue, N.W., Washington, DC 20418. (202) 334-2855

Additional copies available for sale from: National Academy Press, 2101 Constitution Avenue, N.W. Box 285, Washington, DC 20055. 1-800-624-6242 or (202) 334-3313 (in the Washington metropolitan area). http://www.nap.edu

Printed in the United States of America.

Committee to Identify Potential Breakthrough Technologies and Assess Long-Term R&D Goals in Aeronautics and Space Transportation Technology

R. BYRON PIPES, *chair*, NAE, Rensselaer Polytechnic Institute, Troy, New York
WILLIAM W. HOOVER, *vice chair*, U.S. Air Force (retired), Williamsburg, Virginia
RAMESH K. AGARWAL, Wichita State University, Wichita, Kansas
JACK L. BLUMENTHAL, NAE, TRW Space & Defense Sector, Redondo Beach, California
HEINZ GERHARDT, Northrop Grumman Corporation, Pico Rivera, California
RICHARD S. GOLASZEWSKI, GRA, Inc., Jenkintown, Pennsylvania
EDWARD M. GREITZER, NAE, United Technologies Research Center, East Hartford, Connecticut
R. JOHN HANSMAN, JR., Massachusetts Institute of Technology, Cambridge
CHANTAL JOUBERT, The Boeing Company, Long Beach, California
ANN R. KARAGOZIAN, University of California, Los Angeles
DONALD L. NIELSON, SRI International, Menlo Park, California
ROBERT J. POLUTCHKO, Lockheed Martin Aeronautics Sector (retired), Potomac, Maryland
MARTIN POZESKY, MTP Associates, Potomac, Maryland
RICHARD R. WEISS, Richard R. Weiss Consultant Services, Palmdale, California
TERRENCE A. WEISSHAAR, Purdue University, West Lafayette, Indiana
PETER G. WILHELM, NAE, Naval Research Laboratory, Washington, D.C.

Aeronautics and Space Engineering Board Liaison

WILLIAM H. HEISER, U.S. Air Force Academy (emeritus), USAF Academy, Colorado (until March 1998)

Aeronautics and Space Engineering Board Staff

David A. Turner, Study Director
George M. Levin, ASEB Director
Marvin Weeks, Administrative Assistant

Aeronautics and Space Engineering Board

WILLIAM W. HOOVER, *chair*, U.S. Air Force (retired), Williamsburg, Virginia
A. DWIGHT ABBOTT, Aerospace Corporation, Los Angeles, California
RUZENA BAJSCY, NAE, IOM, University of Pennsylvania, Philadelphia
AARON COHEN, NAE, Texas A&M University, College Station
RAYMOND S. COLLADAY, Lockheed Martin Astronautics, Denver, Colorado
DONALD C. FRASER, NAE, Boston University, Boston, Massachusetts
JOSEPH FULLER, JR., Futron Corporation, Bethesda, Maryland
ROBERT C. GOETZ, Lockheed Martin Skunk Works, Palmdale, California
RICHARD GOLASZEWSKI, GRA, Inc., Jenkintown, Pennsylvania
JAMES M. GUYETTE, Rolls-Royce North American, Reston, Virginia
FREDERICK HAUCK, AXA Space, Bethesda, Maryland
BENJAMIN HUBERMAN, Huberman Consulting Group, Washington, D.C.
JOHN K. LAUBER, Airbus Service Company, Miami Springs, Florida
DAVA J. NEWMAN, Massachusetts Institute of Technology, Cambridge
JAMES G. O'CONNOR, NAE, Pratt & Whitney (retired), Coventry, Connecticut
GEORGE SPRINGER, NAE, Stanford University, Stanford, California
KATHRYN C. THORNTON, University of Virginia, Charlottesville
DIANNE S. WILEY, Northrop Grumman, Pico Rivera, California
RAY A. WILLIAMSON, George Washington University, Washington, D.C.

Staff

George M. Levin, Director

Preface

IMAGINE THE DAY

Imagine the day when aircraft accidents are an order of magnitude less likely to occur than they are today; when noise levels and emissions by commercial aircraft have been reduced by factors of five and four, respectively; when the throughput of the aviation system in all weather conditions is three times today's capacity; when the cost of air travel has been reduced by 50 percent. Imagine the day when the current development cycle time for aircraft has been reduced by half through the use of next-generation design tools and experimental aircraft programs; when 20,000 general aviation aircraft are produced annually; when travel time to the Far East and Europe has been reduced by half at today's subsonic ticket prices. Imagine the day when the cost of launching a payload into low-Earth orbit has been reduced from $10,000 to $1,000 per pound, and then further reduced from $1,000 to $100 per pound.

This vision of the future of air and space transportation reflects the National Aeronautics and Space Administration's (NASA) 10 national goals for aeronautics and space transportation technology in the second decade of the twenty-first century. The task undertaken in this study was to identify revolutionary or breakthrough technologies that could provide the foundation for these achievements. These concepts and technologies also address the future needs and opportunities identified in the National Research Council (NRC) report, Maintaining U.S. Leadership in Aeronautics: Scenario-Based Strategic Planning for NASA's Aeronautics Enterprise (NRC, 1997). A third objective of the study was to assess the feasibility of achieving NASA's 10 goals through either evolutionary or revolutionary developments in technology.

BREAKTHROUGHS ARE REQUIRED

The consensus of the NRC committee and additional experts consulted by the committee during this study is that breakthrough technological capabilities will be required to achieve the vision described in NASA's goals. Consider the past increases in the core power of jet engines, beginning with the 50 hp/lb/sec Von Ohain engines of 1939 and culminating with the F100 engine, with power levels in excess of 250 hp/lb/sec. Because core power is limited by the hydrocarbon stoichiometric limit of approximately 900 hp/lb/sec for current fuels, future advances to achieve the NASA goals for aircraft technology will require revolutionary breakthroughs to reach higher power levels (see Figure P-1).

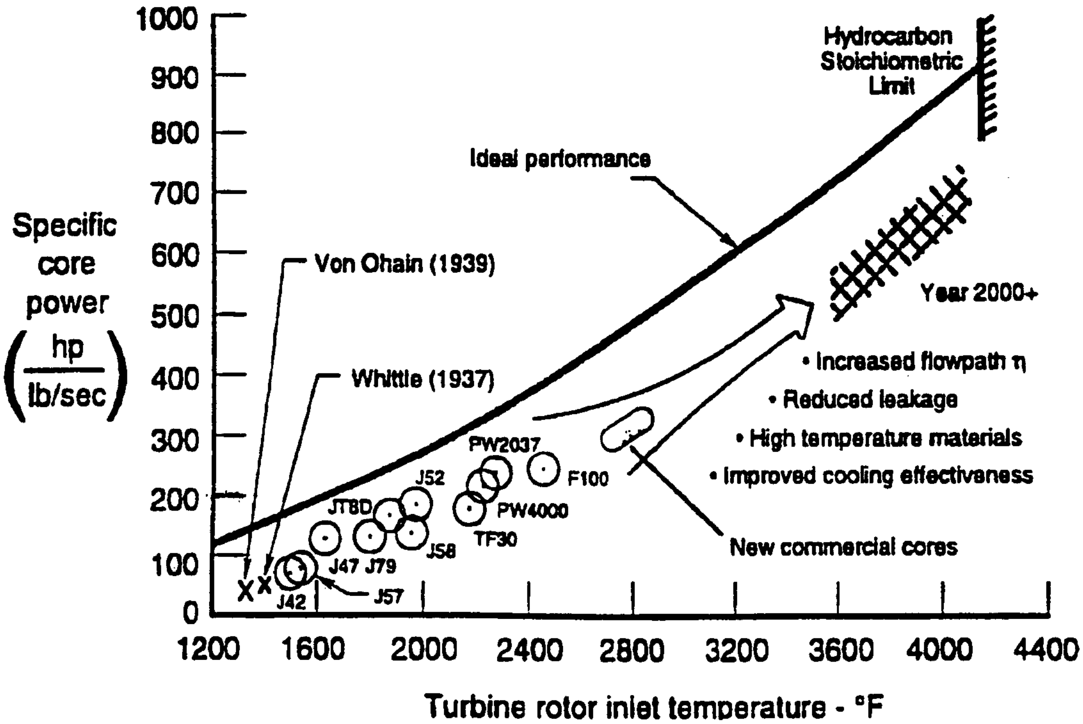


FIGURE P-1 Gas turbine engine core horsepower per pound of core flow versus turbine inlet temperature (showing increase in power enabled by higher turbine temperature capability). The curve marked "Ideal performance" represents the ideal Brayton cycle at maximum work per unit mass flow. Source: Meece, C.E. 1995. Gas Turbine Technologies of the Future. Paper presented at the 12th International Symposium on Air-Breathing Engines, September 10-15, 1995, Melbourne, Australia.

As core power has increased, specific fuel consumption for the turbine engine has been reduced by more than 50 percent from the 1950s to the 1980s. However, further reductions essential to meet the goals for flight economies may not be possible through evolutionary improvements (see Figure P-2).

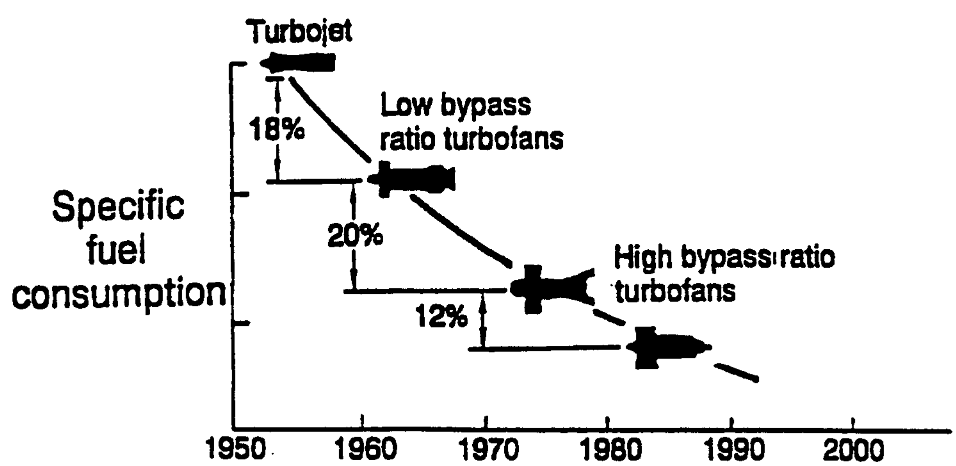


FIGURE P-2 History of thrust specific fuel consumption (unit of fuel consumed per unit of thrust produced). The configuration changes indicate the trend towards higher bypass ratio, resulting in higher propulsive efficiency. Source: Pratt & Whitney.

Launch vehicle services for access to low Earth orbit cost anywhere from $1 million to $1 billion per launch and have never provided customers with launch prices as low as $1,000/lb (see Table P-1). Therefore, reaching this goal and moving beyond it to the goal of $100/lb will require significant breakthroughs in technology.

Table P-1 Approximate Cost per Pound for Major U.S. Launch Vehicles

Vehicle	**Cost Per Pound**	
	Low Earth Orbit	Geosynchronous Earth Orbit
Delta II	$4,500	$25,000
Atlas IIA	$5,800	$29,000
Titan III	$5,000	$28,000
Titan IV-SRMU		
No Upper Stage	$4,600	—
Centaur (upper stage)	—	$26,000

Source: Dawson, T. 1994. Perspectives on U.S. Space Launch Systems—A Staff Background Paper. Washington, D.C.: Subcommittee on Space, Committee on Science, Space and Technology, U.S. House of Representatives.

The accident rate characterized by hull losses for commercial aircraft has not changed significantly since 1970 (see Figure P-3). Yet air traffic is projected to double by the second decade of the twenty-first century. Unless new technologies are introduced, the number of aircraft accidents can also be expected to increase. The primary cause of accidents is flight deck crew error (see Figure P-4). Thus, man-machine interactions and improved pilot situational awareness are promising areas for safety improvements.

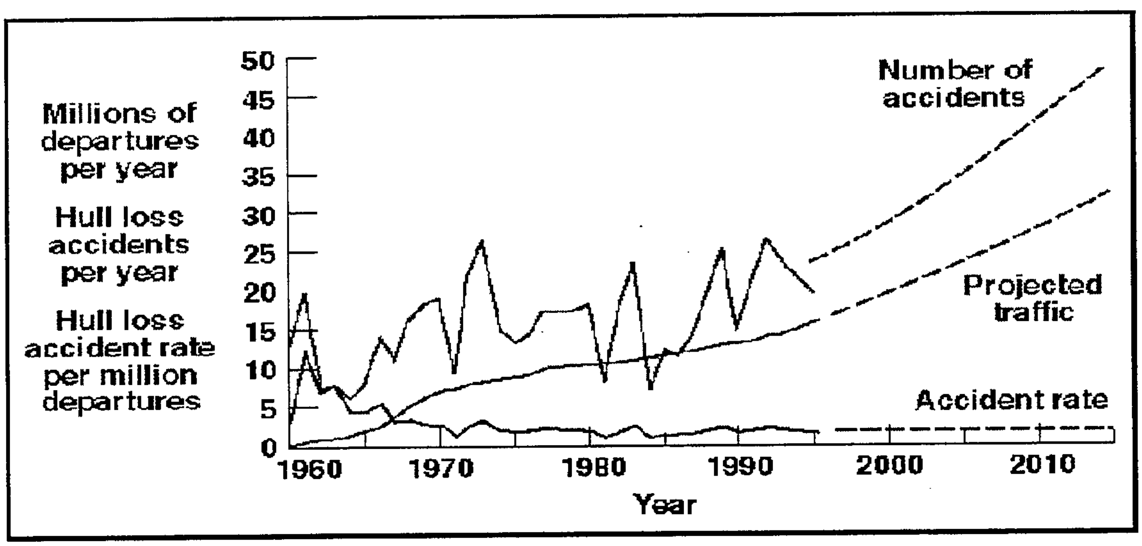


FIGURE P-3 The safety challenge. Source: NASA.

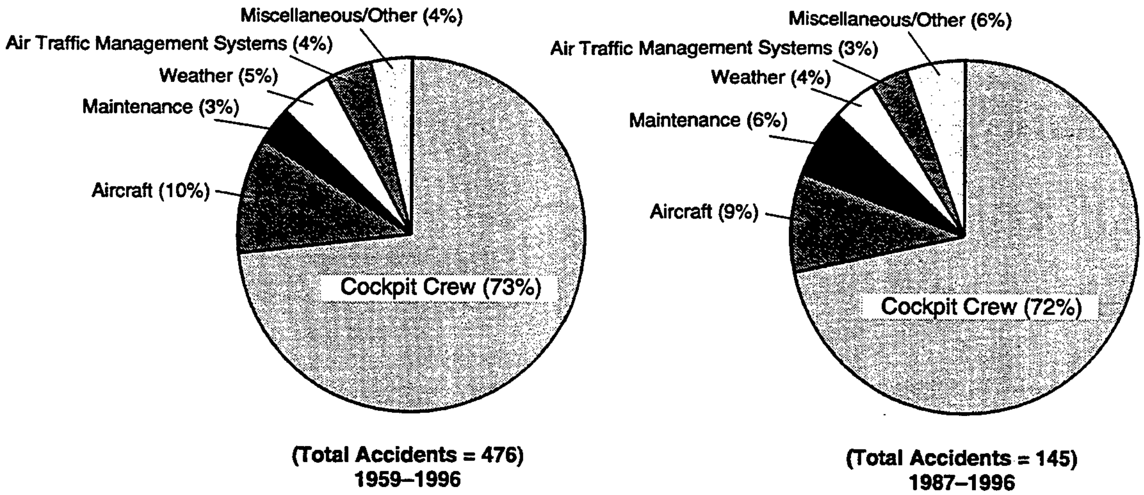


FIGURE P-4 Primary causal factors in worldwide aircraft accidents resulting in total hull loss. Source: The Boeing Company.

INTEGRATION VERSUS BREAKTHROUGHS

Although these examples illustrate the need for breakthroughs in the development of supporting technologies, the committee believes that the integration of existing mature technologies could also contribute to meeting NASA's goals. For example, as we enter the "Information Age," the power of computer simulation and the integration of existing computer-based modeling technologies has become synergistic. Yet there is a growing need to properly validate and certify these design tools. Thus, the science of technology integration will require substantial attention from NASA and the aerospace industry.

R. Byron Pipes, *chair*
William W. Hoover, *vice chair*
Committee to Identify Potential Breakthrough Technologies and Assess Long-Term R&D Goals in Aeronautics and Space Transportation Technology

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Laurence Adams, NAE, Martin Marietta Corporation (retired)
Donald Bahr, NAE, General Electric Aircraft Engines (retired)
Eugene Covert, NAE, Massachusetts Institute of Technology (emeritus)
John Enders, Flight Safety Foundation (retired)
John Fearnsides, The Mitre Corporation
Donald Hart, Don A. Hart & Associates, Inc.
Arthur Kantrowitz, NAS, NAE, Dartmouth College (emeritus)
Nancy Leveson, University of Washington
Donald Lovell, The Boeing Company (retired)
Victor Riley, Honeywell Technology Center
Chester Whitehair, The Aerospace Corporation (retired)

While the individuals listed above have provided constructive comments and suggestions, it must be emphasized that responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The committee would also like to thank each individual and organization that provided information during this study or participated in the workshop.

Contents

List of Tables, Figures, and Boxes

TABLES

FIGURES

BOXES

Executive Summary

After the completion of the National Research Council (NRC) report, Maintaining U.S. Leadership in Aeronautics: Scenario-Based Strategic Planning for NASA's Aeronautics Enterprise (1997), the National Aeronautics and Space Administration (NASA) Office of Aeronautics and Space Transportation Technology requested that the NRC remain involved in its strategic planning process by conducting a study to identify a short list of revolutionary or breakthrough technologies that could be critical to the 20 to 25 year future of aeronautics and space transportation. These technologies were to address the areas of need and opportunity identified in the above mentioned NRC report, which have been characterized by NASA's 10 goals (see Box ES-1) in "Aeronautics & Space Transportation Technology: Three Pillars for Success" (NASA, 1997). The present study would also examine the 10 goals to determine if they are likely to be achievable, either through evolutionary steps in technology or through the identification and application of breakthrough ideas, concepts, and technologies.

The Committee to Identify Potential Breakthrough Technologies and Assess Long-Term R&D Goals in Aeronautics and Space Transportation Technology was formed to conduct this study. Between September 1997 and February 1998, the committee visited the NASA research centers that conduct aeronautics and space transportation research and development (R&D) and was briefed by dozens of members of the aerospace and air transportation communities in government, industry, and academia. After gathering information and collecting ideas from a broad cross section of the aerospace community, the committee organized and conducted a Breakthrough Aerospace Technologies Workshop, which was held on February 19 and 20, 1998, to provide additional input; and assist the committee in assessing the technologies and concepts that had been compiled during the previous five months.

CANDIDATE BREAKTHROUGH TECHNOLOGIES

The committee and the workshop participants adopted a broad definition of "breakthrough technology," which included: (1) discrete technologies that might result in revolutionary improvements in capability; and (2) broad technology areas that might enable dramatic improvements through either evolutionary or revolutionary developments. In addition, the committee and workshop participants recognized that breakthrough capabilities for complex systems, such as air vehicles, launch vehicles, and their related infrastructures, often result from the novel integration of existing "off-the-shelf" technologies, rather than from revolutionary changes or sudden advances in knowledge or techniques.

BOX ES-1

NASA's Three Pillars and Ten Enabling Technology Goals to Achieve National Priorities in Aeronautics and Space Transportation

Pillar One: Global Civil Aviation

Goal 1: Reduce emissions of future aircraft by a factor of three within 10 years and by a factor of five within 20 years.

Goal 2: 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.

Goal 3: Reduce the aircraft accident rate by a factor of five within 10 years and by a factor of 10 within 20 years.

Goal 4: While maintaining safety, triple the aviation system throughput, in all weather conditions, within 10 years.

Goal 5: Reduce the cost of air travel by 25 percent within 10 years, and by 50 percent within 20 years.

Pillar Two: Revolutionary Technology Leaps

Goal 6: Provide next-generation design tools and experimental aircraft to increase design confidence and cut the development cycle time for aircraft in half.

Goal 7: Invigorate the general aviation industry, delivering 10,000 aircraft annually within 10 years and 20,000 aircraft annually within 20 years.

Goal 8: 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.

Pillar Three: Access to Space

Goal 9: Reduce the payload cost to low-Earth orbit by an order of magnitude, from $10,000 to $1,000 per pound, within 10 years.

Goal 10: Reduce the payload cost to low-Earth orbit by an additional order of magnitude, from $1,000's to $100's per pound by 2020.

The candidate breakthrough technologies identified during the workshop were further refined by three subgroups of the committee, which focused on air vehicle technology, air transportation system technology, and space transportation technology. The findings of these three subgroups are summarized in the following sections.

Air Vehicle Technology

Six technology thrust areas were identified as critical to new air vehicle configurations and the achievement of NASA's eight air transportation-related goals.

Advanced Air Vehicle Configurations

Advanced air vehicle configurations that include novel wing designs, drag reduction technologies, and aerodynamic/propulsion integration could lead to substantial progress toward meeting four of NASA's goals: reduced air travel costs; reduced noise and emissions levels; increased aviation system throughput; and high-speed air travel. In general, advanced configurations represent high-risk technologies with potentially high payoffs.

Embedded Sensing and Control

The development of embedded sensors and controls in air vehicles and components could further a number of NASA's air transportation goals. Better health monitoring, more efficient servicing, and improved performance could lead to reduced operating costs and increased safety. In addition, active combustion control in propulsion systems appears to be a promising way to meet NASA's goal for reducing emissions. Critical path items are robust, real-time, highly accurate sensors and actuators.

Structures and Materials

The development of engineered materials, such as low-cost composites and new corrosion-resistant, damage-tolerant alloys, could lead to reductions in life-cycle costs that would enable reductions in the cost of air travel. Engineered materials could also lead to the expansion of the general aviation market through the introduction of new options for designing more efficient and cost-effective aircraft. High-temperature materials for supersonic engines and airframes could also contribute to meeting NASA's goal of reduced travel time.

Advanced Propulsion and Power

NASA's goals related to emissions, noise, cost, general aviation, and high-speed air travel will all be affected by advances in propulsion technology. The major opportunities for breakthrough propulsion technologies include alternative fuels, novel concepts for engine components, active control of propulsion processes, and new power and propulsion devices. The desirability of pursuing any of these technologies to the point of application must be assessed early in their development by assessing their benefits in the context of an overall aircraft system.

Manufacturing

Lower aircraft purchase costs resulting from low-cost manufacturing are necessary for the achievement of NASA's goals of reducing the cost of air travel and reinvigorating the general aviation industry. Lean manufacturing, and automated manufacturing through techniques such as automated and high-velocity machining of parts, sheet metal assembly, and manufacturing by light, should be investigated.

Computer-based Design, Modeling, and Simulation

To reduce the costs and shorten the development cycle for future air vehicles with performance characteristics that meet NASA's air transportation-related goals, substantial improvements will have to be made in computer-based design, modeling, and simulation. These improvements include optimizing the flow of information throughout the design process; enhancing linear and nonlinear simulation capabilities for both aircraft and propulsion systems that fully integrate separate models with varying levels of fidelity; and improving the understanding of the optimal integration of humans and computers throughout the design process.

Air Transportation Systems Technology

Technological changes and the development of new operating procedures for the air transportation system will be required to achieve NASA's air transportation goals. The consensus of the committee is that these improvements will be related in one way or another to advances in information technology.

Models to Predict the Impact of New Technologies and Procedures on the Air Transportation System

The development of models to predict the impact of technological and procedural changes on the air transportation system will be critical to the long-term future of aeronautics and to meeting NASA's goals relevant to system capacity, environmental compatibility, safety, and cost. These models could be used to identify and address barriers to the incorporation of existing and new technologies into the air transportation system. The development of these models would require cooperation among NASA, the Federal Aviation Administration (FAA), and the aviation industry.

Upwardly Compatible Aerospace Information Systems

The expected long lifetimes of current and future aircraft and air traffic management (ATM) systems will necessitate a number of upgrades to their information-based components. To reduce the cost of upgrades that involve new technology or additional functionality, aerospace information systems must be designed to be upwardly compatible. This can be accomplished by developing software that is adaptable, functionally modular, employs an open architecture, and uses well defined interfaces that are unlikely to change. The ability to upgrade information technology-based control systems can contribute to achieving NASA's goals for general aviation, improved safety, reduced operating costs, and increased system throughput.

Methodologies for the Development of High Integrity Software

New software engineering methodologies could facilitate the development, validation, verification, and maintenance of high integrity software. These methodologies include: formal specification methods, including verifiable high-level languages; formal methods of validating specifications and consequent software; techniques for building and checking models to determine the validity of system components, methods of combining disparate sources of software certification evidence; documentation of safety arguments in the form of safety cases; and models of human operators and their roles and expectations. These approaches to software development address NASA's air transportation goals related to improved safety, increased throughput, and a revitalized general aviation industry. Improved software certification would also reduce aircraft costs and design time.

Advanced Human-Automation Systems

Although automation has already improved the safety and increased the efficiency of air travel, additional progress can be made through improvements in aviation-related human-automation systems, such as aircraft flight decks. Key issues that require NASA research support include human-machine task allocation and pilot situation awareness. Advances in technology for uninhabited air vehicles (UAVs) may also contribute to the fulfillment of NASA's safety and capacity goals for air transportation operations involving piloted aircraft.

Precision Air Traffic Management/Aircraft Operations

Precision ATM and aircraft operations will be important to meeting NASA's goals related to air transportation cost, safety, noise and emissions, throughput, high-speed air travel, and general aviation. In the near term, precision ATM will probably be based on emerging technologies now used for weather detection, precise navigation and surveillance, and air-to-ground data transfer and communications. However, achieving NASA's goals in the long term will require the development and implementation of an aircraft-based air traffic control (ATC) capability that is totally independent of ground-based infrastructures.

Mitigating Constraints in Terminal Areas

Increasing air transportation system throughput depends directly on reducing constraints in terminal areas. Technology developments in this area should focus on reducing runway occupancy time, mitigating the effects of aircraft wake vortices, and enabling vertical/short takeoff and landing (V/STOL) aircraft to operate from existing airports and runways without reducing capacity available for other air traffic. To the extent that these improvements can provide more precise control of aircraft operations or can reduce the potentially harmful effects of wake vortices, they could also improve aviation safety and operating conditions for general aviation aircraft. In the long term, personal air transportation vehicles could be a breakthrough that would achieve NASA's throughput goal by allowing millions of air travelers to bypass existing airports and air travel infrastructures. If these vehicles were produced and sold by general aviation manufacturers, NASA's goal of revitalizing this industry could also be met.

Space Transportation Technology

NASA's two goals for access to space reflect the view that low-cost is the key to exploiting the commercial potential of space, as well as to expanding space research and exploration. The committee believes that the predominant low-cost attributes of future launch systems will be simplicity, robust design and operating margins, and hardware reusability. The most practical way to achieve NASA's goals for low-cost access to space is to develop robust, reusable launch systems with aircraft-like maintenance and operations. Six related enabling technology areas are described below.

Advanced Air Breathing Engines

A system study is required to select the most cost effective combined air-breathing/rocket engine for reusable launch vehicles (RLVs). The study must be detailed enough to identify promising technologies and should assess the benefits of engines relative to pure rocket-based propulsion systems incorporating advanced technologies.

Pulse Detonation Wave Engine

Pulse detonation wave engines could provide the equivalent performance of high chamber pressure conventional rocket engines while operating at one-sixth the pressure, representing an increase of 10 to 15 percent in potential specific impulse. Critical technologies for pulse detonation wave engines include scaling limits, process controllability, and fast acting valves for booster-sized engines.

High Thrust to Weight Rocket Engines

The thrust-to-weight ratio necessary to enable rocket propulsion-based RLVs to meet the NASA launch cost goals will require significant reductions in the weight of engine components. Advanced materials and fabrication methods will have to be developed to reduce component weight without compromising performance.

Variable Expansion Ratio Nozzles

Variable expansion-ratio nozzle configurations provide altitude compensation to improve trajectory averaged performance. To be most beneficial to RLVs, these nozzle configurations should be lightweight, should contribute to increases in overall engine thrust-to-weight (T/W), and should reduce overall structural weight requirements.

Advanced Propellants and Storage Methods

Notable improvements in chemical propellants, which could be important to the achievement of NASA's space transportation goals, are possible. Potential advances include the recombination of highly energetic atomic ingredients, hydrogen storage at high effective densities, and the development of metallic hydrogen. However, the potential of these advances may not be realized unless NASA increases its research support.

Integrated Aero-Thermal Structures

For RLVs designed to achieve NASA's launch cost goals, lightweight, integrated aerothermal structures will be critical. System studies should be performed to select the most cost-effective integrated thermostructure. Technology development will also be required for a number of critical subsystems.

Novel Launch System Concepts

Leveraging novel reusable launch vehicle concepts and automated launch operations based on demonstrated technologies and systems approaches aimed at reducing costs and increasing reusability may approach NASA's 10 year launch cost goal.

Additional Goals for Space Transportation

While attempting to identify potential breakthrough technologies that could achieve NASA's space transportation goals, the committee noted that both focus only on achieving low-Earth orbit (LEO). However, this is only one aspect of the space transportation problem. Most satellites that are launched into Earth orbit, even if it is LEO, require some form of upper stage propulsion or orbital transfer vehicle to boost the satellite into an operational orbit. In addition, space vehicles used for scientific exploration must often travel beyond Earth's orbit into deep space. Providing this additional transport will be expensive and will add considerably to the costs of space missions. Thus, the committee suggests that NASA consider modifying the existing goals or adding additional goals to provide "stretch challenges" for:

- reducing the overall cost of space transportation, including the launch stage and the final propulsive stage used in orbital transfer
- minimizing the cost of developing far-reaching space transportation technologies that enable new deep-space missions

BREAKTHROUGH TECHNOLOGIES TO MEET NASA's GOALS

The committee's final deliberations were focused on selecting a short list of breakthrough technologies to recommend to NASA as high priorities. Although all of the technologies listed in the three categories above deserve funding consideration from NASA, the committee realizes that in today's environment of constrained budgets NASA may not be able to support all of them simultaneously. Therefore, the five broad technology areas shown in Figure ES-1 and discussed below are the committee's priority areas of focus for a research and development program that would achieve NASA's 10 goals. The committee believes that these five categories are also suited to NASA's role of "pushing the technological envelope" by supporting the development of high risk, but potentially high payoff technologies that are not likely to be supported by U.S. industry based on conventional commercial investment criteria.

Although the five categories of research and technology development are discussed separately below, they are interrelated in many ways, just as the 10 national goals defined by NASA for air and space transportation are interrelated. To ensure that meeting any one goal does not adversely affect meeting another, technology must be developed with a broad and comprehensive understanding of the entire air and space transportation system. This will require the cooperation of all organizations involved in the nation's aerospace R&D enterprise, including NASA, the FAA, the U.S. Department of Defense (DOD), universities, and industry. However, NASA is well structured and broad-based enough to play a unique role in the analysis and development of technology for the "aerospace" transportation system. Because NASA's R&D programs intersect engineering and risk exploration, the agency is in a unique position to bring insight to the potential synergism and trade-offs of new component insertion, technology integration, and operational interaction. NASA can act as the steward of crosscutting, "system of systems" technology analysis, which could be called enhanced systems engineering.

Cyber Technology

The prefix "cyber, " when used in words such as cybernetics, cybernation, and recent expressions such as cyberspace, connotes a merging of human control over processes and physical activities with computer-based control. For this reason, the committee has chosen the term cyber technology to encompass a host of technologies and concepts related to the growing importance of computer-based information and control systems to air and space transportation and the design and manufacture of aerospace systems.

Cyber technology will be pivotal to the achievement of all of NASA's goals for aeronautics and space transportation technology. However, it would be unrealistic for NASA to play a critical role in R&D related to all of the technologies that fall into this category. For example, continuing improvements in computer microprocessor speed and capability do not require NASA's attention. However, the committee has identified five key cyber technology areas that are crucial to meeting NASA's goals: modeling and simulation for both vehicle design and the characterization of the air transportation system; advanced, robust, real-time sensors and actuators for air vehicle structures, materials, and propulsion systems; automated aerospace manufacturing and space launch operations; improved methods for developing flight-critical software, and optimized human-computer interactions for aircraft flight decks and for the process of aerospace vehicle design. These five areas will not receive adequate levels of R&D focused on aerospace applications without support from NASA.

Recommendation. NASA should focus its aeronautics and space transportation research and technology development to meet the 10 goals on the following areas of cyber technology: modeling and simulation applied to both vehicle design and the characterization of the air transportation system; advanced, robust, real-time sensors and actuators for air vehicle structures, materials, and propulsion systems; increased automation of aerospace manufacturing and space launch operations; improved methods for developing flight-critical software; and improvements in human-computer integration for aircraft operations and aerospace vehicle design.

TABLE ES-1 NASA's Goals for Aeronautics and Space Transportation Technology and the Recommended Breakthrough Technology Categories

Breakthrough Technology Category	Reduced Emissions	Reduced Perceived Noise Levels	Reduced Aircraft Accident Rate
Cyber Technology			
Modeling and simulation	M	M	H
Advanced, robust, real-time sensors and actuators	M	**H**	M
Automated manufacturing	L	L	L
Improved methods for developing flight-critical software	M	M	**H**
Human-computer integration	M	M	**H**
Structures and Materials			
Lightweight structures	L	L	L
High-temperature materials	M	L	L
Propulsion Technology			
Advanced air vehicle propulsion concepts	**H**	**H**	L
Advanced propellants for launch vehicles	—	—	—
Aerospace Vehicle Configurations			
Advanced configurations	M	M	L
Precision Air Traffic Operations in Terminal Areas			
Reduced runway occupancy time	L	—	M
Mitigation of wake vortices	L	—	M
V/STOL air vehicles	L	M	—

L = Low impact on achieving the goal; M = Moderate impact; H = High impact.

Triple Aviation System Throughput	Reduced Air Travel Costs	Increased Design Confidence and Reduced Cycle Time	Invigorated General Aviation Industry	Reduced Travel Time	Reduced Payload Cost to Low Earth Orbit
H	M	**H**	M	M	M
M	M	M	L	L	M
L	M	M	**H**	M	M
M	M	**H**	M	L	—
M	M	**H**	**H**	M	M
L	M	M	**H**	**H**	M
L	M	M	M	**H**	M
L	**H**	L	M	**H**	—
—	—	—	—	—	**H**
M	M	L	M	**H**	M
H	M	—	M	L	—
H	M	—	M	L	—
H	M	—	M	L	—

Structures and Materials

Advances in structures and materials, combined with improvements in computational methods, advances in materials science (including increased understanding of material behavior, characterization, and structural analysis), advances in manufacturing methods (including processing science), concurrent, computer-aided design, and intelligent health/performance monitoring systems will yield substantial benefits for aerospace vehicles. Advances in lightweight structures for RLVs and improvements in the general area of high-temperature materials will be critical to achieving a number of NASA's goals.

Recommendation. Because immediate breakthroughs in the development of lightweight structures and high-temperature materials suitable for high-speed civil transports and reusable launch vehicles are not readily apparent, NASA should invest in fundamental research on structures and materials research, keeping in mind important end use requirements, such as affordability, manufacturability, and maintenance.

Propulsion Technology

Step changes in the gas turbine engine through novel components or through the use of active controls, as well as alternative propulsion systems, may have large payoffs in several areas related to the goals for air transportation. Aspirated compressors with fewer, more slowly turning counter-rotating blade rows, for example, would increase operating margins, improve stall/surge control, and increase thrust-to-weight ratios. Detonation wave engines and fuel cells are examples of promising alternative propulsion and power technologies. These technologies will require a great deal of development before they will be practical for air transportation.

Recommendation. NASA's investments in propulsion technologies to meet the goals for air transportation should focus on new technologies that offer step changes in the performance of gas turbine engines. NASA should also support research on alternative propulsion and power technologies, which will require aircraft design studies as early in the development process as possible to assess potential benefits.

The committee believes that rocket-based or combined rocket/airbreathing propulsion systems will continue to be the technology of choice for the commercial launch industry. Therefore, technology breakthroughs in propellant performance, density, and affordability are imperative for meeting NASA's space transportation goals. Technologies that should be investigated cooperatively by NASA and the Air Force include cryogenic solid hydrogen, metallic hydrogen, carbon and carbon-boron absorptivity of hydrogen, and cryogenic solid oxygen.

Recommendation. To reduce launch costs, NASA should become a full partner with the U.S. Air Force in the development of advanced rocket propellants. This joint program should focus on cryogenic solid hydrogen, metallic hydrogen, the carbon and carbon-boron absorptivity of hydrogen, and cryogenic solid oxygen.

Aerospace Vehicle Configurations and Integration Concepts

The overarching necessity for the total integration of component technologies in the development of air vehicles will require that both conventional and unconventional configurations continue to be explored in pursuit of NASA's goals. However, the committee believes that R&D on unconventional advanced configurations deserves NASA's support because of their high potential for meeting the goals.

Recommendation. NASA should continue to support preliminary feasibility studies for advanced air and launch vehicle configurations designed with new levels of propulsion/airframe/aerodynamic integration. Configurations that have the potential to meet several goals, like the blended-wing-body (BWB), should undergo extensive virtual testing and/or full-scale experimental vehicle development.

Precision Terminal Area Aircraft Operations

The terminal areas of the nation's air transportation system and the air transportation systems of other highly developed areas are fundamentally constrained. No matter how precise navigation and surveillance becomes for air traffic en route from one terminal area to another, total throughput cannot be increased until more commercial cargo and passengers, as well as private aircraft, can take off and land in a terminal area in a given period of time. The committee is not convinced that public use airports will be built or expanded to accommodate projected higher levels of air traffic. Therefore, the solution to increases in terminal area capacity must come from breakthrough technologies and associated procedures.

Reducing terminal area constraints in pursuit of NASA's 10-year goal of tripling aviation system throughput will mean that NASA should focus on the development of technologies and procedures for reducing runway occupancy time, mitigating wake vortices, and increasing the use of V/STOL air vehicles at existing airports. Existing government funded initiatives which are seeking to improve throughput at airports, such as the NASA capacity and terminal area productivity programs, should support R&D in these three areas.

Recommendation. To further the goal of tripling the aviation system throughput in 10 years, NASA should support research and development focused on mitigating terminal area constraints. The most promising areas of focus include the reduction of runway occupancy time, the mitigation of aircraft wake vortices, and the operation of V/STOL air vehicles at existing airports. Existing government-funded initiatives which are seeking to improve throughput at airports, such as the NASA capacity and terminal area productivity programs, should support research and development in these areas.

ACHIEVING THE 10 AND 20 YEAR GOALS

Meeting the 10 Year Milestones

An examination of the average time it takes to embody technology into commercial aerospace products reveals that research and preliminary technology development under way today will probably not be adopted for at least 10 years. Manufacturers and operators have strong economic incentives for maintaining the technological status quo or adopting only incremental changes. However, meeting NASA's goals for aeronautics and space transportation technology will require that concepts, processes, and technologies be incorporated by industry into commercially viable air and space vehicles and related systems.

To accelerate the adoption of new technologies into operational aerospace systems, the committee believes that NASA should focus on the following objectives:

- reducing the risk of technology adoption by ensuring that it has been fully validated and verified
- facilitating technology transfer and the reduction of commercial barriers to technology adoption through increased industry participation in the early stages of technology development
- investigating methods of increasing the pace of the innovation process.

Recommendation. NASA should attempt to reduce the time required to introduce new aerospace technology into the commercial marketplace by supporting technology development to a higher level of readiness, by investigating information technology-based methods to speed the pace of innovation, and by maximizing government/industry collaboration in the development of commercially viable technology focused on the 10 goals.

Meeting the 20 Year Milestones

Although a recommendation that emphasizes technology adoption, technology transfer, rapid innovation, and government/industry collaboration might be misinterpreted as a criticism of long-term, fundamental research, the committee *does not* intend to convey this message. Many of the technologies identified in the remaining chapters of this report are truly high-risk endeavors that will take much longer than 10 years to develop but could eventually meet NASA's goals. Long-term, high-risk technologies should be pursued through research that is focused specifically on the achievement of the 20 year milestones.

The committee also recognizes that many appropriate technologies to achieve these long-term milestones have not been identified because ideal solutions to the challenging problems they represent are currently unknown. The committee believes that the general knowledge pool of the aerospace community should continue to be increased through fundamental research in order to discover these unidentified technology breakthroughs. Therefore, NASA should ensure that appropriate levels of sustained funding and effort continue to be applied to relatively unfocused, long-term, fundamental research in the aerospace sciences.

To accomplish these objectives, each NASA center with an aeronautics and space transportation R&D mission should exercise the responsibility and authority to fund researchers with promising ideas that could lead directly to the accomplishment of one or more goals or could eventually lead to revolutionary new aerospace technologies.

Recommendation. NASA should ensure that appropriate levels of sustained funding and effort continue to be applied to R&D focused specifically on the 10 goals, and to more general long-term, fundamental research in the aerospace sciences. To accomplish this, each NASA research center with an aeronautics and space transportation technology mission should exercise the responsibility and authority to fund researchers with promising ideas that could lead directly to the accomplishment of one or more goals or could eventually lead to revolutionary new aerospace technologies.

1

Introduction

EVOLUTION OF THE 10 AERONAUTICS AND SPACE TRANSPORTATION TECHNOLOGY GOALS

The National Aeronautics and Space Administration (NASA) has developed 10 goals for the application of technology to air and space transportation (see Box 1-1). These goals were developed through a strategic planning process that involved a number of sources of information.

The National Science and Technology Council's Aeronautics Goals

In 1995, the National Science and Technology Council (NSTC) released a report calling for action to ensure that the United States maintains a strong and competitive aeronautics industry (NSTC, 1995). This report was the third in a series of reports released by the Executive Office of the President calling for the pursuit of national goals in aeronautics research and technology by government, industry, and academia (OSTP, 1985, 1987). The three specific goals discussed in the 1995 report are listed below:

- maintain the superiority of U.S. aircraft and engines
- improve the safety, efficiency, and cost effectiveness of the global air transportation system
- ensure the long-term environmental compatibility of the aviation system

NASA's Strategic Planning in Response to the NSTC Goals

After the release the 1995 NSTC report, NASA, which is chartered by the National Aeronautics and Space Act of 1958 in part to "preserve the role of the United States as a leader in aeronautical science and technology and the application thereof," initiated a strategic planning process in response to the three goals. The preliminary plan, released by the NASA Office of Aeronautics in 1995, attempted to characterize aviation in the year 2020 and described several types of aerospace systems and technologies that might be in use (NASA, 1995). However, this was only a preliminary vision based on the judgments of NASA aeronautical experts who extrapolated current trends in aviation and aeronautics.

BOX 1-1

NASA's Three Pillars and Ten Enabling Technology Goals to Achieve National Priorities in Aeronautics and Space Transportation

Pillar One: Global Civil Aviation

Goal 1: Reduce emissions of future aircraft by a factor of three within 10 years and by a factor of five within 20 years.

Goal 2: 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.

Goal 3: Reduce the aircraft accident rate by a factor of five within 10 years and by a factor of 10 within 20 years.

Goal 4: While maintaining safety, triple the aviation system throughput, in all weather conditions, within 10 years.

Goal 5: Reduce the cost of air travel by 25 percent within 10 years and by 50 percent within 20 years.

Pillar Two: Revolutionary Technology Leaps

Goal 6: Provide next-generation design tools and experimental aircraft to increase design confidence and cut the development cycle time for aircraft in half.

Goal 7: Invigorate the general aviation industry, delivering 10,000 aircraft annually within 10 years and 20,000 aircraft annually within 20 years.

Goal 8: 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.

Pillar Three: Access to Space

Goal 9: Reduce the payload cost to low-Earth orbit by an order of magnitude, from $10,000 to $1,000 per pound, within 10 years.

Goal 10: Reduce the payload cost to low-Earth orbit by an additional order of magnitude, from $1,000's to $100's per pound, by 2020.

Scenario-Based Strategic Planning Workshop

Recognizing that a long-term strategic plan for aeronautics requires a broad-based national perspective that includes the needs of users and consumers of aerospace products, the NASA Office of Aeronautics asked the National Research Council (NRC) to conduct a workshop that would bring together experts from industry, government, and academia to analyze a number of scenarios for aeronautics 15 to 25 years hence. A steering committee was formed under the auspices of the NRC Aeronautics and Space Engineering Board to plan, organize, and conduct the workshop and report on its conclusions. This constituted phase 1 of the current study. The results of the workshop, which analyzed five future world scenarios developed in collaboration with a core team of individuals from the NASA Office of Aeronautics, The Futures Group, and the Systems Technology Group of Science Applications International Corporation, were summarized in Maintaining U.S. Leadership in Aeronautics: Scenario-Based Strategic Planning for NASA's Aeronautics Enterprise (NRC, 1997).[1] The five scenarios used at the workshop, based on variations of four socioeconomic dimensions, are summarized in Figure 1-1.[2]

Dimensions								
U.S. Economic Competitiveness		Worldwide Demand for Aeronautics Products and Services		Threats to Global Security and/or Quality of Life		Global Trend in Government Participation in Society		
Strong	Weak	High Growth	Low Growth	High	Low	Low	High	Scenarios
x		x			x	x		Pushing the Envelope
x			x	x			x	Grounded
	x	x		x			x	Regional Tensions
	x	x			x	x		Trading Places
	x		x	x			x	Environmentally Challenged

FIGURE 1-1 The five scenarios and four dimensions.

Note: *U.S. economic competitiveness* is the relative share of internationally traded products and services in the world economy (strong or weak). *Worldwide demand for aeronautics products and services* is the level of demand for aeronautics products and services related to civil, military, and access to space applications in local, regional, and global markets (high growth and low growth). *Threats to global security and/or quality of life* are direct threats to the health and safety of people and/or the stability and viability of governments and their implications for the United States (high or low threat). *Global trend in government participation in society* is the tendency of government to regulate and/or intervene in key aspects of society and the economy (high or low).

---

[1] This report can be viewed on the following world wide web site: http://www.nap.edu/readingroom/records/0309056969.html

[2] Altering four dimensions with two values each creates a total of 16 possible scenarios. Five of the scenarios were selected by the steering committee, the core team, and the senior leaders in NASA's aeronautics enterprise for further analysis at the workshop.

Participants in the NRC workshop were divided into five working groups, or "world teams," that "lived" in one of the five worlds for the duration of the workshop in order to develop a comprehensive view of the role of aeronautics and space transportation technology in that scenario.[3] An iterative round-robin process was also used to assess the applicability of various technology categories to multiple scenarios. The final list of aerospace technology needs and opportunities is summarized in Table 1-1.

TABLE 1-1 Robust, Significant, and Noteworthy Needs and Opportunities

ROBUST Common to all scenarios	SIGNIFICANT Less common but vital to some scenarios	NOTEWORTHY Specialized and unique
Air Traffic Management satellite-based, autonomous, tailored	Access to Space small payloads, low cost, on demand	Short-to-Medium Range Aircraft V/STOL, commuter, infrastructure independent, military special operations
Airport Infrastructure constrained, austere, tailored	Supersonic Aircraft long range, large, and low capacity	Stealth Aircraft evade terrorist threats, quiet over populated areas
Safety/ Survivability significant accident reduction, survive natural and man-made threats	Subsonic Aircraft large, small, long and short range	General Aviation increased activity, part of a customer-tailored air transportation system
Manufacturing agile, virtual, validation, certification	Air Cargo large, low-cost, specialized, and reconfigurable aircraft	Tailored and Smart Materials reduced fuel consumption and enhanced safety
	Uninhabited Air Vehicles weapons, surveillance, intelligence	Microelectro Mechanical Systems (MEMS) reduced fuel consumption and vehicle size
	Environment noise, emissions, hydrogen fuels	Sonic Boom Mitigation enable supersonic flight over populated areas
	Security Systems airport, aircraft, terrorist threat	
	Vertical/Short Takeoff and Landing (V/STOL) Aircraft short, medium, and long range, stealth, infrastructure independent, military special operations	
	Skilled Training and Education distributed and tailored training	

[3] Prior to the NRC workshop, but after the initiation of the study, NASA requested that access to space also be considered by the workshop's participants to reflect organizational restructuring that placed space transportation technology development in the Office of Aeronautics. The organization was subsequently renamed the Office of Aeronautics and Space Transportation Technology.

Parallel NASA Activities Leading to the 10 Goals

The results of the NRC's scenario-based strategic planning workshop were carefully scrutinized during a two week workshop sponsored by NASA and attended by representatives of the Office of Aeronautics and Space Transportation Technology and the NASA centers responsible for aeronautics research and technology development. This workshop selected a number of goals applicable to air and space transportation technology, which were then reviewed by members of the aerospace industry and the NASA administrator, leading to the final selection of 10 goals under three pillars shown in Box 1-1. Other parallel activities related to air and space transportation, such as the White House Commission on Aviation Safety and Security (the Gore Commission), also influenced the final selection and wording of the goals (Gore, 1997).[4]

The brochure, "The Three Pillars of Success for Aviation and Space Transportation in the 21st Century" (NASA, 1997), describing the 10 aeronautics and space transportation goals was released to the public during a speech by NASA Administrator Daniel S. Goldin on March 20, 1997, in Washington, D.C.

THIS STUDY

Statement of Task

After the completion of the NRC report, Maintaining U.S. Leadership in Aeronautics: Scenario-Based Strategic Planning for NASA's Aeronautics Enterprise (NRC, 1997), the NASA Office of Aeronautics and Space Transportation Technology requested that the NRC continue to guide the agency's strategic planning process by conducting a study to identify a short list of revolutionary, or breakthrough, technologies that could be critical to the 20 to 25 year future of aeronautics and space transportation, based primarily on the areas of need and opportunity identified in the Phase I study. These technologies should represent high risk, but potentially very high payoff, investments that would be appropriate components of NASA's advanced basic research and development (R&D) program (see Appendix A). The study would examine NASA's long-term aeronautics and space transportation R&D goals, which have since been published in the brochure, "Aeronautics & Space Transportation Technology: Three Pillars for Success" (NASA, 1997).

Study Approach

A committee was formed to undertake the study under the auspices of the NRC Aeronautics and Space Engineering Board during the summer of 1997. Appendix B contains brief biographies of the committee members. At the first meeting, held on

[4] Personal communication from Robert Pearce, NASA Office of Aeronautics and Space Transportation Technology, March 4, 1998.

September 15 and 16, 1997, the committee familiarized itself with the results of the first phase of the study (NRC, 1997). NASA representatives also provided the committee with an overview of the Aeronautics and Space Transportation Enterprise and the strategic planning process used to develop its R&D portfolio. The committee or smaller working groups held five additional meetings to visit the NASA centers included in the aeronautics enterprise and to be briefed by members of the aerospace and air transportation community in government, industry, and academia (see Appendix C).

The committee also solicited information related to potential breakthrough technologies by creating a web page linked to the internet home page of the ASEB. This home page displayed a letter inviting interested members of the science and engineering community to share their ideas with the committee. Letters were also made available to the attendees of the World Aviation Congress held in Anaheim, California, on October 13 to 16, 1997, and were sent to each invited participant of the scenario-based strategic planning workshop. In addition, invitations to provide information to the committee were sent to each member of the National Academy of Engineering (NAE) in the October 1997 monthly letter from the NAE president to all members.

Workshop on Breakthrough Aerospace Technologies

After gathering information and collecting ideas from a broad cross section of the aerospace community, the committee organized and conducted a Breakthrough Aerospace Technologies Workshop, held on February 19 and 20, 1998, in Washington, D.C. Twenty-two individuals from government, industry, and academia (see Appendix E) attended the workshop, which had two objectives: to provide the committee with additional input; and to help the committee make an initial assessment of the technologies and concepts that had been compiled during the previous five months (see Appendix D). The following assessment criteria were developed for identifying potential breakthrough technologies:

1. The technology will enable future aerospace systems and could potentially lead to the accomplishment of one or more of the 10 aeronautics and space transportation technology goals.

2. The technology is not fully mature. Additional research, development, integration, or validation and verification (V&V) will be required before it can be adopted in commercial aerospace systems.

3. The technology has potential commercial viability in terms of lowering operating costs and does not present significant implementation problems.

4. The development or integration of the technology would be appropriate for NASA's programs. No extensive development of the technology is under way by non-NASA organizations, and the technology is within NASA's charter to "preserve the role of

the United States as a leader in aeronautical science and technology and the application thereof."[5]

The list of technologies developed by the workshop was further refined by several subgroups of the committee. Chapters 2 through 5 are based on the final list. Further deliberations took place at the committee's final meeting on March 23, 1998, and continued until the report entered the formal NRC review process on July 28, 1998. The final deliberations focused on the selection of a short list of breakthrough technologies to recommend to NASA as high priorities that could lead to the eventual achievement of the aeronautic and space transportation technology goals. The list is presented in Chapter 6.

REFERENCES

Gore, Al. 1997. Final report to President Clinton, White House Commission on Aviation Safety and Security, February 12, 1997. Washington, D.C.: Office of the Vice President of the United States.

NASA (National Aeronautics and Space Administration). 1995. Achieving Aeronautics Leadership: Aeronautics Strategic Enterprise Plan, 1995–2000. Washington, D.C.: National Aeronautics and Space Administration.

NASA. 1997. Aeronautics and Space Transportation Technology: Three Pillars for Success. Office of Aeronautics and Space Transportation Technology, Alliance Development Office. Washington, D.C.: National Aeronautics and Space Administration.

NRC (National Research Council). 1997. Maintaining U.S. Leadership in Aeronautics: Scenario-Based Strategic Planning for NASA's Aeronautics Enterprise. Aeronautics and Space Engineering Board, Steering Committee for a Workshop to Develop Long-Term Global Aeronautics Scenarios. Washington, D.C.: National Academy Press.

NSTC (National Science and Technology Council). 1995. Goals for a National Partnership in Aeronautics Research and Technology. Executive Office of the President, Office of Science and Technology Policy. Washington, D.C.: National Science and Technology Council.

OSTP (Office of Science and Technology Policy). 1985. National Aeronautical R&D Goals: Technology for America's Future. Executive Office of the President. Washington, D.C.: Office of Science and Technology Policy.

OSTP. 1987. National Aeronautical R&D Goals: Agenda for Achievement. Executive Office of the President. Washington, D.C.: Office of Science and Technology Policy.

---

[5] National Aeronautics and Space Act of 1958.

2

Achieving NASA's Goals with Breakthrough Technologies

FUTURE AEROSPACE NEEDS AND OPPORTUNITIES AND NASA'S ENABLING TECHNOLOGY GOALS

Readers of this report will note that Chapters 3, 4, and 5, which are focused on air vehicle technology, air transportation system technology, and space transportation technology, respectively, identify technologies within the framework of the 10 NASA goals, rather than the needs and opportunities identified in Maintaining U.S. Leadership in Aeronautics: Scenario-Based Strategic Planning for NASA's Aeronautics Enterprise (NRC, 1997). However, a close examination of NASA's enabling technology goals and the technology needs and opportunities identified during the scenario-based strategic planning workshop reveals that both are focused on the same priorities for the future of air and space transportation: reducing costs, improving performance, enhancing safety, mitigating the constraints of existing infrastructure, and addressing environmental concerns. The relationships between the NASA goals and the broad categories of need and opportunity identified in the previous NRC study are highlighted below.

Enhanced Air Vehicle Safety and Survivability

The NRC steering committee for the scenario-based strategic planning workshop, hereinafter referred to as the phase 1 steering committee, determined that air vehicles of the future must contribute to a significant reduction in aircraft accidents and be able to survive natural and man-made threats. NASA's Goal 3: *Reduce the aircraft accident rate by a factor of five within 10 years and by a factor of 10 within 20 years,* is directly related to this future need.

Environmental Compatibility

Three of the four scenarios analyzed by the phase 1 steering committee revealed a distinct need for more environmentally compatible air vehicles. Goal 1: *Reduce emissions of future aircraft by a factor of three within 10 years and by a factor of five within 20 years,* and Goal 2: *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,* have further defined this important near-term and long-term future need.

General Aviation

General aviation was a major element in only two of the five scenarios assessed by the phase 1 steering committee. However, it is logical to assume that a third scenario, which was characterized by tremendous increases in air travel and economic activity, would include increased general aviation activity. NASA's goal for meeting the future demand for general aviation aircraft is to enable the industry to deliver 10,000 aircraft annually within 10 years and 20,000 aircraft annually within 20 years.

High-Speed Air Travel

The need for high-speed air travel was common to four of the five scenarios examined during the strategic planning workshop. However, the specific requirements for supersonic aircraft varied from one scenario to another. A large, extremely long-range aircraft was considered necessary in some scenarios, whereas a long-range smaller capacity jet used for business travel and specialized cargo delivery was important in other scenarios. Therefore, it is difficult to trace NASA's Goal 8: *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* directly to the needs and opportunities identified through the scenario-based strategic planning workshop. However, the environmental compatibility of supersonic aircraft was considered important in three of the four scenarios. Furthermore, the one scenario that ruled out the need for supersonic air travel did so because of grave concerns about its potential environmental impact. In addition, the phase 1 steering committee raised concerns about noise and the effects of sonic boom. Therefore, NASA's two goals focused on emissions and noise (Goals 1 and 2) are especially relevant to the future development of a high-speed civil transport.

Air Traffic Management and Related Air Transportation System Technology

Just as the future demands for lower costs, improved performance, and enhanced environmental compatibility will require that future air vehicles be improved, the air transportation system they operate within will also have to be improved. Each future scenario had unique implications for the future global air transportation system. In some scenarios, a sophisticated infrastructure was likely to be developed worldwide. In others, most places maintained almost no infrastructure while other places were left with the same basic infrastructure they have today. The volume of air traffic also varied significantly depending on the scenario. Despite these differences, however, it was clear that a safer, more efficient, more flexible, and more sophisticated air traffic management system would be required in the future. The phase 1 steering committee determined that the future air traffic management system should be satellite-based, should operate more autonomously than the system does today, and should be tailored to regional infrastructures and air travel demands.

Three of the enabling technology goals that NASA has defined to guide their R&D into the twenty-first century have a direct relationship to the need for improving the air traffic management system. These are: Goal 3: *Reduce the aircraft accident rate by a factor of five within 10 years and by a factor of 10 within 20 years*; Goal 4: *While maintaining safety, triple the aviation system throughput, in all weather conditions, within 10 years*; and Goal 5: *Reduce the cost of air travel by 25 percent within 10 years, and by 50 percent within 20 years.*

Enhanced Computer-Based Design and Manufacturing

Several of the scenarios assessed by the phase 1 steering committee suggested a future that would include greatly improved modeling and simulation capabilities that could be applied to the entire design and manufacturing process for aerospace systems, from conception to production to operation. "Virtual reality" and related improvements in computers and information systems were considered key enabling technologies. NASA's Goal 6: *Provide next-generation design tools and experimental aircraft to increase design confidence and cut the development cycle time for aircraft in half* is related to this future need, although experimental aircraft were not discussed by the phase 1 steering committee.

Space Transportation Technology

In each scenario, future access to space required low-cost, launch-on-demand vehicles that could carry small satellites (generally less than 500 kilograms) into Earth orbit for a variety of applications. Low cost was the overriding requirement for commercial applications, whereas assured, rapid, and frequent launch-on-demand capabilities were the overriding requirements for military applications.[1]

NASA's two goals for space transportation technology are directly related to the phase 1 steering committee's findings: Goal 9: *Reduce the payload cost to low-Earth orbit by an order of magnitude, from $10,000 to $1,000 per pound, within 10 years*, and Goal 10: *Reduce the payload cost to low-Earth orbit by an additional order of magnitude, from $1,000's to $100's per pound, by 2020.*

DEFINING "BREAKTHROUGH" TECHNOLOGY

After determining that breakthrough technology to meet NASA's goals would fit within the framework of the needs and opportunities identified by the phase 1 steering committee, the

---

[1] The needs of future manned space activities and space science missions were not addressed at the scenario-based strategic planning workshop.

committee also addressed the issue of defining "breakthrough technology." History has shown that breakthroughs, as expressed by order of magnitude improvements in cost, efficiency, or performance, are often apparent only in hindsight and cannot be easily predicted. The committee, therefore, has adopted a broad definition of "breakthrough technology" that includes the following characteristics:

- discrete technologies that might result in revolutionary improvements in capability
- broad technology areas that might realize dramatic improvements in capability through the evolutionary or revolutionary development of a set of contributing technologies

The committee also acknowledges that breakthrough capabilities for complex systems, such as air vehicles, launch vehicles, and related infrastructures, are often the result of the novel integration of existing or "off-the-shelf" technologies, rather than as a result of revolutionary new changes or sudden advances in knowledge or technique.

ACHIEVING THE 10 and 20 YEAR GOALS

Meeting the 10 Year Milestones

The NASA Office of Aeronautics and Space Transportation Technology also asked the committee to examine whether the 10 goals are likely to be achievable, either through evolutionary steps in technology or through the identification and application of breakthrough ideas, concepts, and technologies. The consensus of the committee is that major technological challenges will have to be overcome to meet the goals. Many members of the aerospace community who interacted with the committee were of the same opinion. Concerns about meeting the 10 year milestones were especially strong.

Human ingenuity and the ability to overcome even the most challenging goals cannot be overestimated. The success of the Apollo program in placing a man on the moon less than 10 years after President Kennedy's call to action is a powerful example. The very purpose of setting goals is to motivate people to strive for accomplishments that may seem impossible at first glance. Many NASA senior managers and researchers consider the goals exemplary in this regard.

However, beyond the 10 year timelines for many of the goals and their apparent ability to motivate, there are few similarities between the Apollo program's single goal and the 10 goals for aeronautics and space transportation technology. For example, consider the responsibility for operational implementation. Placing humans on the moon was the sole responsibility of the U.S. government, specifically, NASA. Therefore, technology developed for the Saturn V rocket by government contractors did not have to overcome barriers imposed by the competitive nature of the commercial marketplace, such as manufacturability, maintainability, and affordability, to name a few. In contrast, the concepts, processes, and technologies that are developed with an eye towards meeting NASA's aeronautics and space transportation goals must be incorporated by manufacturers into commercially viable air and space vehicles and related systems before the goals can be achieved. This point was emphasized in a message from the NASA administrator included in the brochure, "Aeronautics & Space Transportation Technology: Three Pillars for Success" (NASA, 1997):

> Throughout the pillars we present "technology goals" which are framed in terms of a final outcome, the anticipated benefit of NASA-developed technology, once it has been incorporated by industry.

An examination of the average time it takes to incorporate new technology into commercial products in the air transportation industry reveals that research and preliminary technology development under way today will probably not be adopted for at least 10 years. Manufacturers and operators of commercial transport aircraft have strong economic incentives to maintain the technological status quo or to adopt only incremental changes (GRA, 1992). The large base of existing aircraft and installed aircraft subsystems, coupled with existing infrastructure, also promotes the use of existing technology. New technologies that are not imposed by regulation must compete on a cost basis with existing components, which are usually relatively low cost and efficient.[2]

A similar economic argument can be made for the commercial space launch marketplace, where the basic design of expendable rockets has not changed dramatically since World War II. Therefore, any breakthrough technology that is important to the achievement of NASA's 10 year goals will have to evolve from existing, market-proven technologies.

The committee believes that NASA can take several steps to try to accelerate the adoption of previously unapplied technology into operational aerospace systems: (1) reduce the risk of technology adoption through increased validation and verification; (2) facilitate technology transfer and reduce commercial barriers to technology adoption by increasing industry participation in the early stages of technology development; and (3) investigate methods of increasing the pace of the innovation process itself.

Reducing the Risk of Technology Adoption

NASA has adopted a metric known as the technology readiness level (TRL) to measure progress towards the maturation of a given technology. The nine TRLs and their definitions are shown in Box 2-1. NASA's involvement in the development of aerospace technology usually ends at TRL 6: *System/subsystem model or prototype demonstrated/validated in a relevant environment*. Thus, NASA has not validated or verified a given technology in a realistic operating environment before industry is expected to integrate the technology into a new vehicle or associated system. The economic risk of adopting new technology for

[2] Non-economic barriers to the adoption of new technology in the air transportation system are discussed in Chapter 4.

airlines and aircraft manufacturers could be reduced and implementation accelerated if NASA played a stronger role in technology demonstration and validation. Industry would have more incentives to adopt new technologies that contribute to the accomplishment of the 10 goals if NASA carries their development activities through at least TRL 7: *System prototype demonstrated in flight environment.*[3]

BOX 2-1
NASA's Technology Readiness Levels

1	Basic principles observed and reported
2	Technology concept and/or application formulated (candidate selected)
3	Analytical and experimental critical function or characteristic proof-of-concept or completed design
4	Component and/or application formulated (candidate selected)
5	Component (or breadboard) verification in a relevant environment
6	System/subsystem (configuration) model or prototype demonstrated/validated in a relevant environment
7	System prototype demonstrated in flight
8	Actual system completed and "flight qualified" through test and demonstration
9	Actual system "flight proven" in operational flight

Accelerating the Adoption of Commercially Viable Technology

Most manufacturers attempt to shorten the design-to-market timeline for new products by automating much of the design, development, and production process. NASA may be able to assist the aerospace industry by applying advances in information technology to unique aerospace problems. (Research and technology issues related to enhancing the capabilities of modeling and simulation are discussed in Chapter 3 and Chapter 4; and automated manufacturing is discussed in Chapter 3.)

The time-to-market for commercial products that incorporate technology originally developed in government laboratories can also be shortened by addressing issues such as reliability, manufacturability, maintainability, safety, affordability, and certification, as early as possible in the development cycle. This means that early industry involvement in R&D will be essential. Therefore, NASA should explore organizational models that maximize collaboration with industry throughout the innovation process.[4] In fostering increased

[3] In the development of space transportation technology, NASA is currently investing in technology demonstration vehicles, such as the X-33 and X-34, in partnership with industry.

[4] The NASA Advanced General Aviation Transport Experiments Consortium, focused on R&D for general aviation, is a useful example (NASA, 1996).

collaboration with industry, NASA should ensure that the joint R&D activities maintain a focus on the 10 year goals, rather than shorter term objectives that often dominate industry's own technology development programs.

Finding. Unless NASA can reduce the time required to introduce new aerospace technology into the commercial marketplace, the 10 year milestones can only be achieved with evolutionary technologies.

Recommendation. NASA should attempt to reduce the time required to introduce new aerospace technology into the commercial marketplace by supporting technology development to a higher level of readiness, by investigating information technology-based methods to speed the pace of innovation, and by maximizing government/industry collaboration in the development of commercially viable technology focused on the 10 goals.

Meeting the 20 Year Milestones

Although a recommendation that emphasizes technology adoption, technology transfer, rapid innovation, and government/industry collaboration might be misinterpreted as a criticism of long-term, fundamental research, the committee *does not* intend to convey this message. Many of the technologies identified in the remaining chapters of this report are truly high-risk endeavors that will take much longer than 10 years to develop but could eventually meet NASA's goals. Long-term, high-risk technologies should be pursued through research that is focused specifically on the achievement of the 20-year milestones

The committee also recognizes that many appropriate technologies to achieve these long-term milestones have not been identified because ideal solutions to the challenging problems they represent are currently unknown. The committee believes that the general knowledge pool of the aerospace community should continue to be increased through fundamental research in order to discover these unidentified technology breakthroughs. Therefore, NASA should ensure that appropriate levels of sustained funding and effort continue to be applied to relatively unfocused, long-term, fundamental research in the aerospace sciences.

To accomplish these objectives, each NASA center with an aeronautics and space transportation R&D mission should exercise the responsibility and authority to fund researchers with promising ideas that could lead directly to the accomplishment of one or more goals or could eventually lead to revolutionary new aerospace technologies.

Finding. The pursuit of long-term, high-risk technology development is essential to meeting the 20 year milestones and will require continued NASA support of fundamental research in the aerospace sciences.

Recommendation. NASA should ensure that appropriate levels of sustained funding and effort continue to be applied to R&D focused specifically on the 10 goals, and to more general long-term, fundamental research in the aerospace sciences. To accomplish this, each NASA research center with an aeronautics and space transportation technology mission should exercise the responsibility and authority to fund researchers with promising ideas that could lead directly to the accomplishment of one or more goals or could eventually lead to revolutionary new aerospace technologies.

REFERENCES

GRA. 1992. Economic Analysis of Aeronautical Research and Technology: An Update. Jenkintown, Pa.: GRA, Inc.

NASA. 1996. (Re)inventing Government-Industry R&D Collaboration. NASA Technical Memorandum 110271, Bruce J. Holmes. Hampton, Va.: NASA Langley Research Center.

NASA. 1997. Aeronautics and Space Transportation Technology: Three Pillars for Success. Office of Aeronautics and Space Transportation Technology, Alliance Development Office. Washington, D.C.: National Aeronautics and Space Administration.

NRC. 1997. Maintaining U.S. Leadership in Aeronautics: Scenario-Based Strategic Planning for NASA's Aeronautics Enterprise. Aeronautics and Space Engineering Board, Steering Committee for a Workshop to Develop Long-Term Global Aeronautics Scenarios. Washington, D.C.: National Academy Press.

3

Air Vehicle Technology

TOWARDS NEW AIR VEHICLES

Airliners in the current fleet resemble the configurations introduced more than 40 years ago, with cylindrical fuselages, moderately-swept wings, and externally mounted engines. These configurations have benefited from gradual and continuous improvements based on advances in aerodynamics, structures and materials, and, above all, propulsion technology, and gradual improvements are expected to continue. However, it will be difficult to meet the aggressive NASA goals (in terms of both vehicle attributes and timing) for air transportation cost, efficiency, and environmental compatibility with traditional transport aircraft configurations because they are already highly optimized in design. Therefore, NASA should encourage the exploration of alternative transport configurations, which will require a creative, multidisciplinary approach that closely considers the interactions among airframe, propulsion systems, structural concepts, and control systems.

The development of advanced configurations for air vehicles is an obvious avenue towards meeting NASA's goals, but it is not the only avenue. In this regard, it is useful to classify air R&D into three types. The first is the creation of configurations that look radically different from present configurations. These advanced configurations may have the greatest potential for improvements, but they will also require the most long-term R&D focused on an in-depth understanding of systems integration. The blended-wing body (BWB) is a good illustration. The second category of R&D is focused on vehicle subsystems, such as propulsion systems, that can be applied to advanced air vehicle configurations or to configurations that resemble current configurations although new developments may greatly alter the way they operate. The third category involves major breakthroughs in the processes associated with vehicle development, such as manufacturing and design, which would, for example, enable substantial reductions in cost. These processes could be used for both existing and advanced air vehicle configurations. A major advance in any of these categories, alone or in combination with an advance in another category, may meet one or more of NASA's goals for air transportation.

TECHNOLOGY THRUST AREAS

In this chapter the committee proposes six critical technology thrust areas for new air vehicle configurations that could achieve NASA's eight air transportation-related goals.

- **advanced air vehicle configurations**—designs with reduced weight, improved aerodynamic performance, and highly integrated airframe/propulsion systems that are substantially different from current air vehicle configurations. Advanced configurations could have a major impact on reducing the cost of air travel and improving the aviation system throughput and could enable the development of a high-speed civil transport aircraft that would reduce travel time to the Far East and Europe.

- **embedded sensors and controls**—intelligent gas turbine engines that can control aeroacoustic, aerodynamic, aerothermodynamic, and aeromechanical instabilities, and aircraft with embedded active control systems for controlling loads, reducing drag, and monitoring health. Embedded sensors and controls could reduce noise, emissions, and costs through more effective diagnosis and maintenance processes.

- **structures and materials**—low-cost composite materials, including the manufacturing processes associated with them, new corrosion-resistant, damage-tolerant alloys, and engineered and smart materials. Advanced structures and materials could lead to reduced fabrication and life-cycle costs and reduced travel time (by enabling economically viable commercial supersonic flight) and could expand the general aviation market by creating more options for designing efficient, cost-effective aircraft.

- **advanced propulsion and power**—innovative approaches to gas turbine engines with substantially fewer parts and enhanced performance through active control. This technology area could also include propulsion systems with no rotating components (such as pulse detonation wave engines), alternative engine concepts, and alternative fuels. Advanced propulsion and power technologies could contribute to reductions in noise, emissions, air travel cost, and travel time (with high-speed commercial flight).

- **advanced manufacturing**—automated manufacturing, including precision manufacturing, automated assembly, and fabrication by light, as well as further applications of lean manufacturing techniques. The major impact of advanced manufacturing would be to reduce the cost of commercial aircraft and possibly the cost of general aviation aircraft.

- **computer-based design, modeling, and simulation**—virtual design and testing that could replace, or at least greatly reduce, the time and cost of testing aircraft and propulsion systems and could provide the capability for multidisciplinary design optimization and virtual prototyping. Enhanced modeling and simulation could further NASA's goals related to the cost of air travel, air vehicle design time, general aviation, and high-speed air travel. If models of the air traffic management (ATM) system are included, this technology area could also advance the goals related to safety and throughput.

The impact of these six thrust areas on the eight NASA goals associated with air vehicle technology is illustrated in the matrix shown in Table 3-1. The goals are the horizontal rows, and the technology thrust areas are the column headings.

TABLE 3-1 The Six Air Vehicle Technology Thrust Areas and NASA's Eight Air Transportation-Related Goals

	Advanced Air Vehicle Configurations	Embedded Sensors and Control Systems	Structures and Materials	Advanced Propulsion and Power	Advanced Manufacturing	Modeling and Simulation
Emissions	L	M	M	H	L	M
Noise	M	H	M	M	L	M
Safety	L	M	L	L	L	H
Throughput	M	M	L	L	L	H
Travel Cost	H/M	M	H/M	H	H/M	H/M
Design Time	L	M	H/M	L	H/M	H
General Aviation	M	L	H	M	H	H
Travel Time	H	L	H	H	H	H

L = Low impact on achieving the goal. M = Moderate impact. H = High impact.

Advanced Air Vehicle Configurations

This first technology area involves exploring new vehicle design concepts that are based on the overarching necessity for the total integration of component technologies in the development of air vehicles. In addition to benefits, most new technologies create penalties, such as increases in weight or cost or decreases in reliability. The payoff of a new technology must be evaluated in terms of its influence on a complete configuration. The importance of this configuration-driven systems analysis cannot be overemphasized.

In addition to the exploration of full vehicle configurations, two aspects of advanced vehicle design that cut across a number of proposed configurations warrant special attention: (1) advanced technologies for reducing drag and (2) novel methods of increasing vehicle performance through more effective integration of the propulsion system and airframe to maximize aerodynamic efficiency.

Advanced Configurations

One example of a radically different configuration from current subsonic commercial transport aircraft is the BWB (blended-wing body) being investigated by Boeing and NASA. The BWB is a useful example of the performance level that may be achievable from novel designs. The BWB concept, shown in Figure 3-1, is a large commercial transport design that improves aerodynamic performance by joining hitherto separate aircraft components, such as engines, wings, and fuselage, into a unified frame (Liebeck et al., 1998). Some of the potential advantages of this design over existing designs are shown in Table 3-2. Aircraft purchase prices are directly related to operating empty weight; therefore, a 12 percent reduction in weight will mean a corresponding 12 percent reduction in the initial purchase price, assuming that manufacturing costs remain the same.[1] A 27 percent reduction in fuel consumption would also reduce fuel costs, which currently accounts for about 15 percent of total airline costs. Reductions in fuel consumption will also mean lower levels of engine emissions and noise compared to conventional aircraft carrying the same number of passengers over the same distance.

The twin-fuselage/midwing configuration is another example of an unconventional design, but unlike the BWB, it has not been studied in any detail. However, this design deserves renewed consideration because of a number of inherent advantages. For example, the outboard fuselages are detachable to provide logistical flexibility, and the empennages are designed to recoup some of the energy from the wing-tip vortex and convert it into thrust to offset the high induced drag of the short-span center wing. The center wing can be designed with a lightweight structure, because the wing bending moments are reduced through the counteracting inertial loads of the fuselage masses. A lightweight wing structure would lower empty operating weight compared to the weight of a conventional aircraft with equivalent range and cargo capacity.

Although both of these concepts look promising, the adoption of either one as a commercial transport aircraft is unlikely until their viability can be proven under actual flight conditions. Existing air transportation system rules would also have to be modified to accommodate the operating procedures these new configurations would require. Other

[1] Manufacturing processes are discussed later in the chapter.

advanced concepts, including the box wing and the strut-braced wing, should also be assessed for their potential to meet NASA's goals.

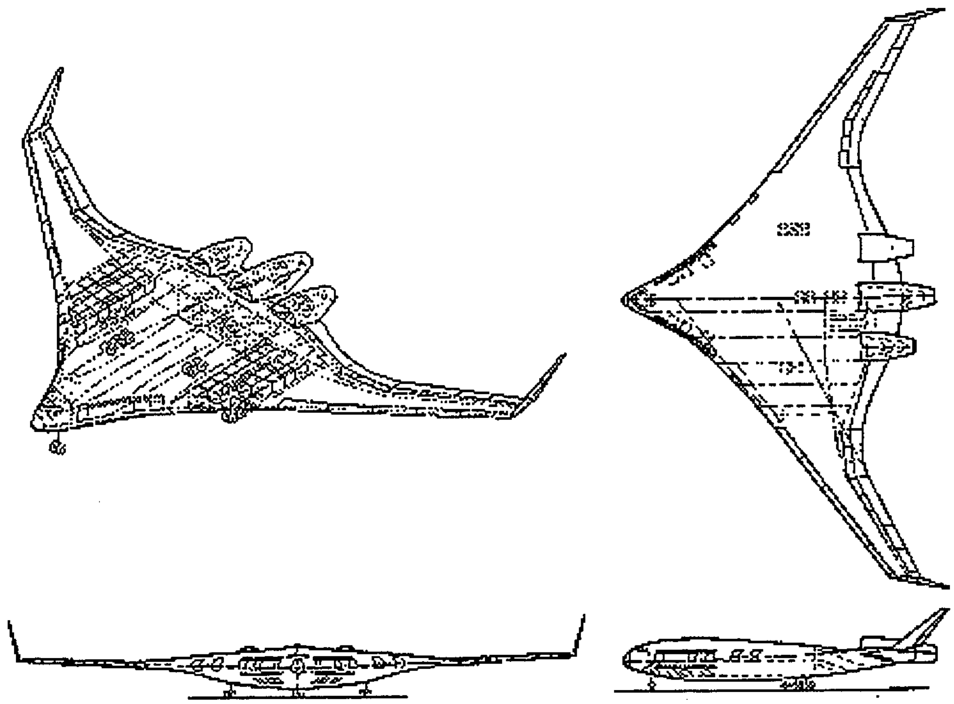


FIGURE 3-1 Isometric view of the BWB airplane. Source: The Boeing Company

Drag Reduction Technologies

Meeting the goal of establishing supersonic air travel at current subsonic travel prices will require improvements in aerodynamic performance through the reduction of drag. Some concepts, such as the generation of a weak plasma flow field to weaken shock strength and laminar flow control, have been shown to have some benefit, but they have not been adopted for use on commercial aircraft because of uncertainties about their costs versus their potential benefits. The integration of these techniques within a supersonic aircraft will have to be investigated before the cost/benefit trade-offs can be determined.

The potential for reducing a supersonic aircraft's shock wave as a means of reducing drag is currently being investigated in a joint NASA/Air Force project. Interest in this concept stems from reports in the Russian literature indicating that the shock structure in a weakly ionized gas at high temperature (plasma) is significantly weaker than in nonionized gases at the same temperature. If this phenomenon can be confirmed, and if interference with communications and sensing equipment is not a problem, shock waves could potentially be reduced during supersonic flight by projecting a weakly ionized plasma flow field into the airflow directly in front of the aircraft. Although operational issues, such as the power requirements for plasma generation, may make this idea applicable only in the long term, its technical promise for mitigating sonic boom should be explored now.

TABLE 3-2 Performance Comparison between the Boeing/NASA BWB and a Baseline Conventional Aircraft Configuration with Equivalent Component Technologies [a]

	Conventional Baseline Aircraft	Blended-Wing Body	Improvement
Passengers	800	800	—
Range (nautical miles)	7,000	7,000	—
Takeoff gross weight (lbs)	970,000	823,000	15% lower
Operational empty weight (lbs)	470,000	412,000	12% lower
Fuel consumption	294,000	213,000	27% lower
Lift/Drag ratio at cruise	19	23	20% higher
Wingspan (ft)	235	280	—
Wing area (trap)	6,100	7,840	—
Total Thrust (lbs)	4 x 63,600	3 x 61,900	27% lower
Thrust/Weight ratio	0.262	0.226	—
Thrust specific fuel consumption	0.466	0.466	—

[a] Fair comparisons between the BWB and existing commercial transport aircraft are theoretical because no 800 passenger airliners are currently operating.

Aerodynamic/Propulsive Integration

One way to explain the potential benefits of airframe/propulsion integration is to consider the phenomena of flight using the surrounding air as the frame of reference rather than the air vehicle. The issue of interest is how the airframe affects the airstream. Minimizing the residual disturbances of the airframe and propulsion system on the airstream, which will improve overall aerodynamic performance, requires a higher degree of airframe/propulsion integration. Wake-ingesting propulsion system configurations (which increase the efficiency of the propulsion system) and devices that mitigate wing-tip vortices (possibly by placing engines on wing tips) could be components of integrated aerodynamic/propulsive systems. It may also be useful to investigate the potential for distributed propulsion, either through electric motors powered by fuel cells or, possibly, arrays of much smaller propulsion devices, such as microengines. If these devices were placed along the trailing edge of the wing, they might reduce profile drag and control lift in addition to providing propulsion.

Finding. Advanced air vehicle configurations that include novel wing designs, drag reduction technologies, and aerodynamic/propulsion integration could lead to substantial progress toward meeting four of NASA's goals: reduced air travel costs; reduced noise and emissions levels; increased aviation system throughput; and high-speed air travel. In general, advanced configurations represent high-risk technologies with potentially high payoffs.

Embedded Sensors and Controls

Embedding sensors and actuators in the subcomponents of air vehicles, such as the airframe structure and the gas turbine engine, will allow many physical properties to be monitored and controlled in a manner that would improve performance and reliability and should advance NASA's air transportation goals. NASA can contribute to this area of technology by supporting the development of new sensors and actuators and the signal processing capability required to use sensors and actuators together.

Aircraft with Controlled "Adaptive" Structures

Controlled "adaptive" structures include a wide variety of structural concepts that could be useful for both air and space vehicles. Applications include aerodynamic and acoustic load control and reconfiguration and load control in response to structural damage to flight systems. Controlled adaptive structures will not only reduce weight, but should also contribute to aircraft safety and reliability.

Although the development of lower cost, more reliable new sensors and actuators could lead to breakthroughs in the design of air vehicle configurations by allowing designs with marginal vehicle stability and greater flexibility, the most important near-term and midterm application of controlled structures is the monitoring and management of vehicle health. Structural health monitoring and diagnostics add "nerves" to the aircraft system that continuously sense the health or "state" of an aircraft's structure during operation. Parameters include characterization of load spectra for individual components, detection of damage, and monitoring of the severity of damage to determine if repairs are needed, either on the ground or in flight.

Real-time, onboard health monitoring can provide important safety-related information to both operations planners and pilots. The miniaturization and packaging of nondestructive testing equipment, perhaps through the use of microelectro mechanical systems (MEMS), for the onboard detection of cracks or other damage could alert pilots to structural or engine damage before it becomes critical. This information could also be acquired, stored, and re-acquired, either in flight or on the ground, where it could be retrieved by maintenance organizations, making inspection and repairs less costly and time consuming.

Even though rudimentary health monitoring and management systems are already in use on some military and commercial aircraft, breakthroughs are needed to make these systems more capable. Sensors must be reliable and small enough to be embedded in or attached to a structure, and they must be inexpensive to buy and maintain. Advances are also needed in network, processor, and data storage technology, as well as signal processing capability.

Intelligent Gas Turbine Engines: Moving from Proof of Concept to Deployment

Gas turbine engines are highly optimized and tightly constrained propulsion systems that operate near a number of operational limitations. Improvements in performance often come from small (although hard won) changes in design boundaries. One idea that may allow step improvements is much greater use of closed-loop feedback control either to take better advantage of existing operating margins or to move the operational boundaries. The words "closed-loop feedback" imply a range of possibilities, including concepts such as designing engine operation to maximize life, monitoring engine conditions to enable retirement for cause, and actively controlling aerodynamic and aeromechanical instabilities, such as surge, rotating stall, flutter, main combustor instability, and instabilities associated with after-burner systems. In addition, intelligent gas turbine engines have the potential to reduce noise, either through active noise control or through the direct management of noise sources, perhaps by tailoring rotor wakes. The increased number of robust, versatile sensors may also improve (with suitable system identification techniques) the monitoring of engine health (both preventive and reactive), which could decrease overhaul costs, prevent unwanted in-flight events, and increase safety.

Closed-loop processes could also be used to reduce emissions. Two important pollutants in aircraft emissions are nitrogen oxides, or NO_X (mainly NO, and to a lesser extent, NO_2) and carbon monoxide (CO). NO, the major contributor to NO_X, is mostly generated by a thermal mechanism, which means that the higher the temperature of the combustion process (or the closer to local stoichiometric conditions), the higher the NO emissions. To reduce NO_X, engines must operate very lean through a staged-combustion process. CO, however, is not converted to CO_2 when the reaction is quite lean or cool, so low NO emissions often mean high CO emissions. Figure 3-2, which shows the formation of NO_X and CO as functions of temperature, illustrates this trade-off.

The challenge is to tailor the reaction process to allow an engine to operate lean enough overall (or in stages) to reduce NO but not so lean that the CO emissions increase significantly. This could potentially be achieved with closed-loop engine controls with real-time, detailed, diagnostic sensors, such as optical or MEMS-based sensors. If it were possible to know the local species and temperature distributions at several key locations in real time, this information could be distilled into a few parameters, such as mixture and temperature pattern factor, that could be used as input to a closed-loop controller with "actuators" that control fuel jet injection characteristics, staging characteristics, and dilution jets. This type of active control could also improve fuel-air mixing during the combustion process, which would also lead to a reduction in the emission of "unburned" hydrocarbons.

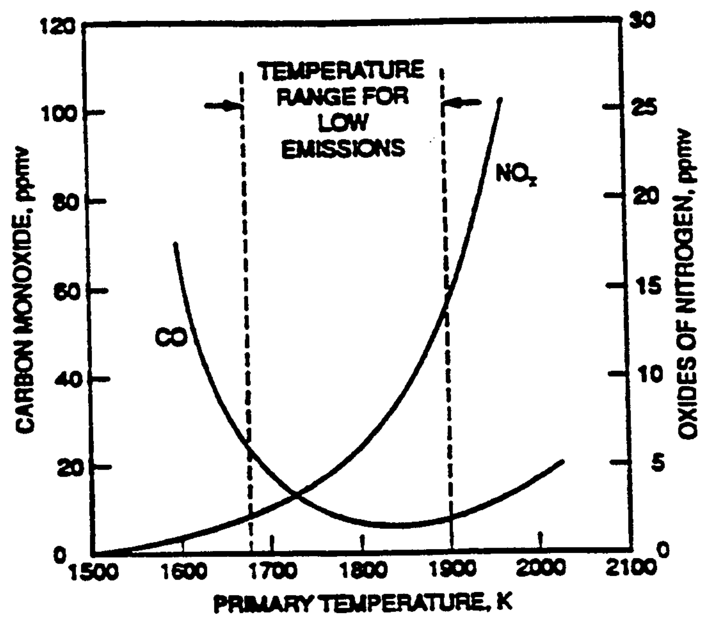


FIGURE 3-2 NO_x and CO formation in gas turbine combustion as a function of temperature. Source: Lefebrve, 1995.

The development of active control for individual engine components will require robust, real-time sensors and actuators. Current actuation and sensing devices operate in an engine at the macroscopic level. Distributed sensors and actuators that operate at the microscale will have to be much more robust than current optical sensors or silicon-based MEMS.

Research (mostly in universities) on active control of unsteady flow in gas turbines has had encouraging results in long-standing problem areas, including active stall stabilization and the control of combustion instability. From the viewpoint of an engine manufacturer, however, there is an enormous gap between results in a laboratory test facility and a flight-worthy, economically attractive, operational propulsion system. Universities are not well placed to bridge this gap, but NASA can play a key role in making intelligent engines a reality. This will require not only research on controls, structures, and fluids, but also a willingness to examine, and to address, the technological barriers inherent in the flight certification process.

Finding. The development of embedded sensors and controls in air vehicles and components could further a number of NASA's air transportation goals. Better health monitoring, more efficient servicing, and improved performance could lead to reduced operating costs and increased safety. In addition, active combustion control in propulsion systems appears to be a promising way to meet NASA's goal for reducing emissions. Critical path items are robust, real-time, highly accurate sensors and actuators.

Structures and Materials

The airframe structural weight of long-range transport aircraft comprises about 35 to 40 percent of the takeoff gross weight. Engine weight comprises 15 to 20 percent, and systems/equipment weight (e.g., avionics and air conditioning) comprise another 10 to 15 percent. Aircraft components, such as the engine turbine and compressor, have benefited from advances in materials technology, and major advances in manufacturing and design have produced a more reliable, higher quality airframe. The structural weight fraction of transport aircraft airframes has remained fairly constant over the past 30 years, not because of a lack of progress in structural technology, but because other aircraft components have also benefited from advanced technologies and have maintained their weight fraction values. Engineered materials may offer solutions for continued advancements in airframe structures

Engineered materials are specially designed combinations of materials, either in solution (alloys) or distinct (filamentary carbon/polymeric matrices), that take advantage of superior features of their components. For instance, advanced composites contain lightweight materials, such as carbon fibers, which are brittle but can be processed with a matrix, a resin, or even a metal to minimize the density of flaws that could lead to failures. A matrix can be used as a binder to hold the fibrous material together and act as a load transfer mechanism.

Advanced Composites

Advanced composite structures first appeared more than 30 years ago, but their promise has been largely unrealized in commercial air transport airframes. Although they have high strength-to-weight and high stiffness-to-weight ratios, their failure modes are different from those of conventional metallic materials. Despite decades of study, some failure modes are still poorly understood and unpredictable, which has limited the widespread application of composites in air vehicles.

Because advanced composites are both a material and a microstructural system, they can be designed to control load paths, a capability almost as important as the material's intrinsic low weight. For example, the X-29 research aircraft was the first manned air vehicle to orient, or "tailor," advanced composite directional strength and stiffness to reduce weight and prevent adverse aeroelastic interactions between the wing bending and aircraft flight mechanics modes. Less advanced composite materials, such as fiberglass/epoxy, have been used in small kit-built airplanes because of the ability to fabricate low-cost, smooth, strong airframes. Nevertheless, the high cost of advanced composites is still a major problem limiting their use.

Advanced Metal Alloys

Other engineered materials include advanced alloys, such as those used in high-temperature turbine blades. These materials are solutions of different elements, each of which brings a superior performance attribute to the material system. Engineered materials may have a thin coating deposited or engineered onto the blade surface to resist surface abrasion and wear or to provide thermal properties unavailable from a single material. Deposition schemes can now construct a coating only a few atoms thick and virtually free of defects so that its strength approaches the cohesive strength of an atomic bond. Advanced metal alloys have been developed from extensive, time-consuming, "cut-and-try" research, and making the process less empirical to reduce cost and time will be important.

Other recent improvements in the properties of metals have been achieved by engineering materials, even ordinary substances, such as aluminum or aluminum alloys, at the microstructural level. This is done by purifying and processing to minimize grain size, intermolecular and intergranular distortions, and imperfections. Additional improvements should be possible by alloying any of a wide variety of substances, such as metals and ceramics, and varying the processes to tailor the final material properties. These developments will be the result of continuing work in ultrafine particle metallurgy, plasma jet sprays, and vapor coatings. Newer methods, such as the laser stream method, could lead to "fabrication by light," whereby complex parts and assemblies could be manufactured by depositing material from a wire spool, using a highly accurate, high-powered laser.

Applications of engineered materials include tough, high-temperature materials for efficient, small gas turbines and internal combustion engines used for general aviation aircraft or for the development of large supersonic gas turbines applicable to high-speed civil transports. Engineered materials could also increase attachment efficiency by reducing the number of necessary fasteners. The weight of joints and fittings could also be reduced using "graded" structures that begin as one engineered material and end as another.

Finding. The development of engineered materials, such as low-cost composites and new corrosion-resistant, damage-tolerant alloys, could lead to reductions in life-cycle costs that would enable reductions in the cost of air travel. Engineered materials could also lead to the expansion of the general aviation market through the introduction of new options for designing more efficient and cost-effective aircraft. High-temperature materials for supersonic engines and airframes could also contribute to meeting NASA's goal of reduced travel time.

Advanced Propulsion and Power

The development of advanced power and propulsion systems will have an impact on achieving NASA's air transportation goals for emissions, noise, safety, air travel cost, general aviation, and high-speed air travel. Advanced engine configurations, and even concepts that could be directly implemented into existing propulsion systems, may require revolutionary advances in specific scientific areas. Therefore, this area of technology merits NASA's long-term focus.

Alternative Fuels

Alternative fuels could improve safety and reduce or eliminate NO_X, CO, and carbon dioxide (CO_2) emissions. The TWA Flight 800 tragedy has raised concerns about the flammability limits of conventional hydrocarbon fuels, such as Jet A. To address these safety concerns, advanced formulations of existing aviation fuel types specifically tailored to achieve appropriate flammability limits should be explored. Alternative aviation fuels, such as hydrogen fuels, also warrant increased attention because emissions of CO, CO_2, and sodium dioxide (SO_2) , are not produced when hydrogen is burned. CO_2 is a primary product of the hydrocarbon combustion process, and its contribution as a "greenhouse gas" to global warming is considered to be significant. Therefore, nonhydrocarbon fuels, such as hydrogen, should be explored as a logical alternative.

Hydrogen fuels also have the potential to reduce NO_X emissions because hydrogen has a wide flammability range that allows for the sequential combustion of lean and rich air/hydrogen mixtures. The energetic potential of hydrogen, which is 2.7 times greater than that of most hydrocarbon fuels, is another incentive for the development of hydrogen fuel.

Safety is a major concern in handling hydrogen fuel, but it actually might be safer in the event of an aircraft accident. As NASA studies have shown, the strong buoyancy of hydrogen flames could lead to the quick dissipation of a hydrogen fire, increasing the potential survivability of passengers inside the fuselage (Brewer et al., 1981).

The major challenge to the use of hydrogen as a common aviation fuel is the lack of nationwide and worldwide infrastructures to support safe and efficient fuel generation, transport, and airport handling/aircraft refueling. However, these issues are being studied in Europe and Canada, and NASA should keep abreast of progress in this area. A second challenge to the use of cryogenic hydrogen is its extremely low density—about one-fifth of that of conventional jet fuels. The large amount of required aircraft fuel tankage (which must be pressurized and insulated) would require major changes in the basic design features of aircraft. However, advances discussed in chapter 5, such as gelled hydrogen and the storage of hydrogen in a carbon nanofiber matrix with an ultra-high capacity to absorb/adsorb hydrogen gas, could eventually eliminate tankage problems.

Novel Engine Components

Improvements in the performance of individual engine components can be achieved through current research on magnetic bearings, variable-geometry components, and passive noise and flow control through novel component designs. The aggressive use of closed-loop flow controls for external as well as internal flows should also be investigated.

Another promising area of research concerns novel methods of controlling flows in aeropropulsion and fluid machinery components. Examples include suction within the inlet and suction and blowing in nozzle/ejector components for improved tonal noise control, as well as controlled suction in "aspirated" compressor blades and end-wall surfaces for increased operating margins, stall/surge control, and thrust-to-weight ratios. Recent conceptual studies on the development of so-called "aspirated" compressors combine aspiration and counter-rotating blade rows (thus causing a higher relative velocity in the rotating blade rows) to yield engines with nearly doubled thrust-to-weight ratios and compressor-stage counts decreased by a factor of two to three (Epstein and Waitz, 1997). Innovative methods for managing viscous flows will be important to the development of aspirated compressors.

Novel Power/Propulsion Devices

The air-breathing engine configurations currently in use (turbojets, turbofans, turboprops, and ramjets) or being tested (scramjets) will take future aircraft designs well into the next century. Novel power generation devices, some of which are still in the embryonic stage of development, also look promising. These devices could be used in advanced air vehicles to generate auxiliary power or in an entirely new engine configuration.

Fuel Cells. Fuel cells should be studied as a potential power source for subsonic aircraft propulsion and power systems. Electric motors powered by fuel cells could be used to drive propulsive fans. Presently, the power density of fuel cells is more than an order of magnitude less than the power density of turbofan engines operating at sea level. However, at high altitude, the power density differences are greatly diminished because fuel cells can retain their power generating capacity at altitude. Furthermore, the chemical power conversion efficiency of fuel cells is about twice as high as the thermodynamic power conversion efficiency of standard propulsion systems. Because hydrogen provides 2.7 times more energetic potential than hydrocarbon fuel, hydrogen fuel cells could reduce consumption five-fold over the standard gas turbine engine. However, the storage of an adequate volume of hydrogen remains a critical issue.

Lithium-air fuel cells are a potential source of nonpolluting power, especially for general aviation and light military aircraft. One recent study has shown that a standard 225 horsepower propulsion system for a light airplane could be replaced with an electric motor and lithium-air fuel cell power plant that would have roughly the same power, endurance, and weight (Galbraith, 1996). The power generation process of a lithium-air fuel cell produces no emissions. The by-product of the electrochemical process is lithium hydroxide, which could be retained aboard the aircraft and recycled after flight to retrieve the reusable metallic lithium.

NASA should support aircraft design studies to investigate the integration of fuel cell propulsion technologies. Favorable results could then be the basis of technology development in other areas in which NASA has expertise, such as alternative fuels and new materials.

Microscale Engines and Components. Ultrasmall-scale (micron to millimeter) air-breathing and rocket engines and engine elements, such as heat exchangers, are also at the embryonic stage, with research being pursued at only a few universities and research laboratories. However, the implementation of microscale devices is an exciting prospect, not only as propulsors, but also as miniature thermal cycles for generating energy and environmental control on systems, such as satellites.

Advanced Supersonic/Hypersonic Engine Concepts. The elimination of complicated rotating machinery in aircraft propulsion systems appears to be a worthwhile goal. The detonation-wave engine is one approach that eliminates moving parts. Detonation-wave engine technology demonstrations are being pursued, to a limited extent, by NASA and the Air Force through the Small Business Innovative Research Program. The theoretical advantages are based on the thermal efficiency benefits of the Humphrey cycle over the turbine engine Brayton cycle. Pulse detonation wave (PDW) or oblique detonation wave (ODW) engines may have the potential to increase specific impulse levels. Technological challenges are the stability of detonation in the ODW engine and control in the PDW engine. Although high noise levels are another serious disadvantage, these engine concepts have potential applications for high-speed aircraft.

Finding. NASA's goals related to emissions, noise, cost, general aviation, and high-speed air travel will all be affected by advances in propulsion technology. The major opportunities for breakthrough propulsion technologies include alternative fuels, novel concepts for engine components, active control of propulsion processes, and new power and propulsion devices. The desirability of pursuing any of these technologies to the point of application must be assessed early in their development by assessing their benefits in the context of an overall aircraft system.

Advanced Manufacturing

Low-cost manufacturing is the foundation of low-cost vehicles and propulsion systems and is based on improvements in both processes and economies of scale. Production quantities in aviation typically limit what can be achieved through economies of scale, but as automated manufacturing equipment becomes less specialized and more versatile, it is possible to foresee breakthroughs that allow small production runs to benefit fully from automation, without exacting the enormous cost of specialized automation equipment. Lower aircraft purchase costs resulting from low-cost manufacturing should contribute to NASA's goal of reducing the cost of air travel. In addition, reductions in the cost of new general aviation aircraft could further the achievement of NASA's goal to reinvigorate this sector of the aerospace industry.

Manufacturing is an essential element of aerospace product development and should influence the design of air vehicles, starting with conceptual design. Manufacturing is a key ingredient in the process of computer-based design, modeling, and simulation, which are discussed in the next section. NASA can support the integration of manufacturing into the whole air vehicle production and development process by investigating automated fabrication processes, such as manufacturing by light and high-velocity machining, that could directly link design databases to finished assemblies.

Automated Manufacturing Processes

Labor and associated overhead are the two largest elements in the cost of airframes which in turn is a major factor in the costs of aircraft and air travel. Automated manufacturing entails eliminating the extensive hands-on labor currently required to fabricate parts, assemble airframes, and perform quality inspections. Concepts that enable automated manufacturing and, therefore, a breakthrough in cost, include automated assembly, precision manufacturing, and fabrication by light.

Automated Assembly. Recent progress has been made in the automated assembly of composite structures using filament winding; oriented, chopped-fiber spray systems; and automated tape or tow placement machines. Presently, however, high material costs still limit the application of automated composites. Continued efforts to reduce costs would be worthwhile.

The automation of sheet metal assemblies is another area NASA should pursue. Except for the automatic riveting of flat or moderately curved panels, sheet metal assembly is still a manual operation. Sheet metal structures are assembled with mechanical fasteners (e.g., rivets and screw fasteners) or adhesive bonding. Rivets are typically driven or squeezed, but expensive blind fasteners are used if the inside of the structure is not accessible. An airframe built entirely with blind fasteners is usually too heavy and too costly, so the automation of riveted sheet metal assembly will require a breakthrough in the development of automatic equipment that can drill, seal between panels, align parts, and set rivets on complex structural shapes. One key challenge is gaining access to tight areas in recessed corners, with sufficient jigging to hold contours during assembly operations.

Bonded assemblies would also benefit from automation. Using machines to place precision-formed parts automatically into bonding fixtures would reduce costs and eliminate potential variations in quality that result from manual handling of the bond lines and adhesives.

High-Velocity Machining. High-velocity machining of unitized parts has a high probability of reducing assembly costs by eliminating the need for special tooling and large quantity production. In the long run, high-velocity machining may replace standard sheet metal or composite assemblies. This emerging technology enables the fabrication of large monolithic structural parts cut out of metal blocks that are lighter, stronger, and easier to join to other airframe components. The parts are highly accurate and have smooth surfaces that require little finishing. Walls and ribs can be as thin as 20 to 30 thousandths of an inch thick.

This new manufacturing technology increases metal cutting speeds by a factor of seven or more, with high-power tool spindles running at 25,000 rpm and cutters that advance 600 to 700 inches per minute across the metal block. Metals cut at such high speeds are locally transformed into a plastic state, and the heat produced is carried away by the chips leaving the workpiece cool and undistorted. The development of tool spindles driven by a 100 hp turbine and turning at 100,000 rpm is proceeding. This technology is currently being applied to the cutting of aluminum. Application to titanium and other advanced metallic materials is the next logical step.

Precision Manufacturing. Aluminum continues to be a material of great utility for aerospace applications, but the forming of aluminum parts demands both skill and numerous trials to achieve an acceptably "repeatable" process. The many variabilities of parts require considerable handwork in the assembly jigs to align, reform, and shim them for the best fit. Methods and software for analyzing the forming process are available, but empirical factors and adjustments are still required, which have been barriers to economical automation.

Environmental factors, material variability, and the effects of coiling for storage are all important to the repeatability of forming processes. Improving our understanding of these so precision formed parts can be produced without numerous setup trials would allow the development of adaptable forming equipment based on computer-aided design data and material sample properties to adjust the forming operation. This breakthrough would result in considerable cost savings from reductions in machine time, labor, and the amount of scrap.

Manufacturing by Light. Manufacturing by light is a novel fabrication process that imitates, in a sense, biological growth. Finished parts are obtained in one step from a computer-aided design database. The process, which is currently under development, is also called laser forming and laser engineered net shaping. In this solid, free-form fabrication process, a metal powder, specifically titanium powder, is fused, layer by layer, with a computer-controlled high-power laser to produce high-quality shapes without the use of tools. The mechanical properties are reported to be equivalent or superior to those of wrought titanium. The benefits for large titanium parts include substantial reductions in material cost, machining cost, first-article time, and cycle time. Parts made with other advanced metallic materials, if developed, could also be produced using this fabrication process, which could reduce material costs and machining costs.

Lean Manufacturing

Lean manufacturing is based on five principles: specifying value from the point of view of the customer, identifying the value stream for each product, creating continuous flow in manufacturing and assembly, making products flow only to meet customer demand, and striving for perfection. Lean manufacturing focuses on removing nonvalue-added tasks from the process or processes of interest. Lean manufacturing was pioneered by the Toyota company and is now being adapted to the production of aircraft as a means of cutting costs, reducing cycle times, and improving quality.[2] Lean processes can also be extended to the manufacture of propulsion systems and, perhaps, to aspects of the development process, such as testing.

Finding. Lower aircraft purchase costs resulting from low-cost manufacturing are necessary for the achievement of NASA's goals of reducing the cost of air travel and reinvigorating the general aviation industry. Lean manufacturing, and automated manufacturing through techniques such as automated and high-velocity machining of parts, sheet metal assembly, and manufacturing by light, should be investigated.

Computer-Based Design, Modeling, and Simulation

Aircraft technology is highly optimized. Therefore, reductions in operating costs, and improvements in efficiency and environmental compatibility through more efficient engines, lighter weight materials, and enhanced aerodynamic performance have been difficult to achieve while maintaining reasonable development costs and product cycle times. Furthermore, cost issues sometimes become clear only at an advanced stage of design when they are difficult to address or resolve. Multidisciplinary simulation and optimization tools that produce better designs more rapidly and at lower cost would accelerate the introduction of new technologies into air vehicle designs, thus accomplishing NASA's goal to provide the tools necessary for increasing design confidence and reducing the development cycle time, while simultaneously contributing to the achievement of other goals related to air transportation.

Optimizing the Design Process

Much of current design process is sequential and iterative, requiring months (sometimes years) to develop to a final production design. Sometimes expensive delays are caused by time lags in the transfer of data from one discipline to another, which are often physically isolated and have different methods of analysis. Methodologies that can integrate several

[2] The Lean Aircraft Initiative, which is managed by the Massachusetts Institute of Technology and involves government agencies, labor groups, and defense aerospace businesses, began investigating the application of lean practices to the aerospace industry in 1993.

disciplines concurrently would make earlier optimization feasible and would be a major improvement.

Computers and computer information systems already play a central role in improving an aircraft company's design process in terms of quality and competitiveness. Nevertheless, computer-based optimization and reorganization of the entire design and decision-making process during product development is a research area that could become a victim of company traditions and inertia. Past NASA-sponsored research in this area has led to the development of the DeMaid computer program, which uses "dependency models" to help organizations understand process complexities and reorganize processes to optimize the flow of information and eliminate unnecessary organizational design interactions (Rogers, 1989). Computer-based tools, coupled with better models of the physical elements of vehicles and components, will help to reduce product costs and improve quality.

Creating Nonlinear, Multidisciplinary Aircraft Design Models

Current design tools used in the aircraft industry have several deficiencies, including the use of linear analyses, which are inaccurate for nonlinear (e.g., transonic) flight regimes; and the use of numerous single discipline codes derived from different databases, which makes integration difficult. There is considerable room to improve these tools through the integration of nonlinear computational fluid dynamics (CFD) methods, advanced nonlinear structural analysis methods, and integrated flight and propulsion control models into a single analysis and design system that could be run on advanced parallel computing platforms. The seamless integration of these models, which often have very different levels of fidelity, will require the development of an architecture which currently does not exist. The use of nonlinear methods for CFD, structural analysis, and optimization will also involve several complex, high-risk development efforts. For example, nonlinear optimization will require system-level identification concepts that rely on autoregression or the use of neural networks and fuzzy logic.

Improving Models for Propulsion System Design

The design-to-development process for a jet engine is not only expensive, but also time consuming. It typically takes up to a year longer than the design-to-development cycle for an entire commercial transport aircraft. Therefore, NASA's goal to increase design confidence and cut the development cycle time for aircraft in half is as important to engine manufacturers as it is to airframe builders. Engine manufacturers, in cooperation with NASA, are already investigating computer-based methods for shortening the design-to-development cycle and for reducing costs. The target areas are listed below:

- improved combustion modeling, which includes not only advanced computational procedures, but also reduced order models (including appropriate descriptions of reacting flows) that allow confident preliminary designs of combustors
- predictions of fluid/structure interactions for high-cycle fatigue avoidance (e.g., flutter and resonant stress)
- new methods for identifying aeromechanical and aerodynamic unsteady system responses so that predictions can be rigorously addressed and regimes with high stresses can be identified clearly in the development process
- virtual engine models, with a goal of overnight simulation of a complete engine, which will require developing ways to capture physical processes at an appropriate level of fidelity and rigorous means for passing information between models with different dimensionalities, fidelities, and descriptions.

Optimizing Human/Computer Integration during the Design Process

In addition to reorganizing the flow of information and improving multidisciplinary models for both aircraft and engines, advances in the design process will depend on stimulating human creativity, both teams and individuals, by providing reliable and repeatable computer assistance for tedious, straightforward tasks. Over-reliance on computers and numerical codes to provide data and information, however, can result in burying design flaws in the design process. These flaws have to be exhumed later and create many problems. Mistakes made during conceptualization and preliminary design become increasingly expensive if they percolate through the entire design process before being discovered. Resolving this problem will depend as much on optimizing the integration of humans and computers, as it will on the development of better microprocessors or new software.

Finding. To reduce the costs and shorten the development cycle for future air vehicles with performance characteristics that meet NASA's air transportation-related goals, substantial improvements will have to be made in computer-based design, modeling, and simulation. These improvements include optimizing the flow of information throughout the design process; enhancing linear and nonlinear simulation capabilities for both aircraft and propulsion systems that fully integrate separate models with varying levels of fidelity; and improving the understanding of the optimal integration of humans and computers throughout the design process.

REFERENCES

Brewer, G.D., G. Wittlin, E.F. Versaw, R. Parmley, R. Cima, E.G. Walther. 1981. Assessment of Crash Fire Hazard of LH2-Fueled Aircraft. NASA CR-165525. Washington, D.C.: National Aeronautics and Space Administration.

Epstein, A., and I. Waitz. 1997. Potential Breakthrough Technologies, Propulsion Research at the Gas Turbine Laboratory, MIT. Presentation to the Committee to Identify Potential Breakthrough Technologies and Assess Long-term R&D Goals in Aeronautics and Space Transportation Technology, Cambridge, Massachusetts, November 18, 1997.

Galbraith, A.D. 1996. Electric Propulsion for Light Aircraft: Lithium-Air Fuel Cell for Primary Power. NIAR 96-3. Witchita, Kansas.: National Institute for Aviation Research, Wichita State University.

Lefebrve, A.H. 1995. The Role of Fuel Preparation in Low-Emission Combustion. Journal of Engineering for Gas Turbines and Power. 117(4): 617–654.

Liebeck, R.H., M.A. Page, and B.K. Rawdon. 1998. Blended-Wing Body Subsonic Commercial Transport. AIAA-98-0438. Reston, Virginia.: American Institute of Aeronautics and Astronautics.

Rogers, R.L. 1989. A Knowledge-Based Tool for Multilevel Decomposition of a Complex Design Problem. NASA TP2903. Washington, D.C.: National Aeronautics and Space Administration.

4

Air Transportation System Technology

PARADIGM SHIFT IN THE AIR TRANSPORTATION SYSTEM

Meeting, or even approaching, the aggressive NASA goals for increasing capacity, improving safety, and reducing noise and emissions will certainly require technological improvements to air vehicles like the ones described in Chapter 3. However, breakthroughs in the design and manufacture of airframes and propulsion systems will not be enough. Revolutionary technological changes and the development of new operating procedures, in other words a paradigm shift, will also be necessary in the air transportation system. The consensus of the committee is that this paradigm shift will be enabled by improvements related to advances in information technology.

The six sections that follow describe potential improvements to information-related technologies, such as complex models of the entire air transportation system, robust and upgradable computer software and hardware, communications, navigation, and surveillance systems for ATM and aircraft operations, and externally focused aircraft sensors. New processes and procedures for incorporating these technologies into the system are discussed, as well as the integration of humans and computers in highly automated systems. The effect of these technologies and new procedures on the eight NASA goals associated with air transportation are shown in matrix form in Table 4-1.

MODELS TO PREDICT THE IMPACT OF NEW TECHNOLOGIES AND PROCEDURES

Many of the information-based technologies that could enable major changes to the air transportation system, such as the Global Positioning System (GPS), air-ground datalinks, automatic dependent surveillance (ADS), synthetic vision, and pilot and controller decision aids, have already been developed. However, because of the complex interactions between economic, political, sociological, and technological forces in the air transportation system, it has been extremely difficult to predict the impact of new technologies or changes in operational procedures on operations and safety. Consequently, there is a strong tendency within the system to maintain the status quo, and new technologies or operating procedures have been limited to incremental improvements.

TABLE 4-1 The Six Air Transportation System Technology Areas and NASA's Eight Air Transportation-Related Goals

	Models to predict the impact of new technologies and procedures	Upwardly compatible aerospace information systems	Methodologies for the development of high integrity software	Advanced human-automation systems	Precision air traffic management/ aircraft operations	Mitigating constraints in terminal areas
Emissions	H/M	L	L	L	L	L
Noise	H/M	M	L	M	H/M	M
Safety	H	H	H	H	H	M
Throughput	H	H	H	H	H	H
Travel Cost	H	M	M	M	M	M
Design Time	M	M	H/M	—	—	—
General Aviation	M/L	M/L	H	H	H	M
Travel Time	L	L	M/L	L	M	L

L = Low impact on achieving the goal. M = Moderate impact. H = High impact.

Some new technologies and procedures have been mandated to improve the safety of the overall air transportation system. The adoption of the Traffic Alert/Collision Avoidance System by all U.S. commercial transport aircraft is a prominent example. However, regulations intended to promote safety can sometimes become barriers to technological and procedural changes.[1]

Predicting the impact of technical or operational/procedural changes on a comprehensive basis will require improved methods and models for evaluating the safety of potential changes to the air transportation system. As a basis for the development of methods and models that encompass the technical, procedural, and socioeconomic complexity and dynamism of the system, NASA, industry, and the FAA should prepare a formal representation of existing rules and procedures that govern system operations. The representation should include the rationale for the current rules, how they relate to safety objectives, and how they interact with each other.

[1] For example, many commuter aircraft were designed as 19 passenger aircraft simply because FAA safety regulations require a flight attendant on aircraft designed for 20 or more passengers. This factor impacted aircraft design decisions more than performance or economic improvements that may have been possible from the development of slightly larger aircraft.

Improved models of the air transportation system can further many of NASA's goals. Improved models could lead to more efficient flight routes, for example, which could reduce noise, engine emissions, and operating costs. Improved models of the air transportation system could also shorten design time because they would provide a more accurate representation of existing conditions. Increasing the number of general aviation aircraft would be facilitated by better information about their impact on system capacity, economics, and other parameters. The development of economically viable and environmentally compatible high-speed aircraft also would benefit from a better representation of the current system. The requirements for the development of improved models of the air transportation system are discussed below.

Documentation of the Current System

The current air transportation system, which has evolved over the past eight decades, is now one of the most complex operating systems in the world. The major components are listed below:

- aircraft operated by air carriers, specialized service providers, general aviation enthusiasts, and the military
- public and private airports and intermodal transportation connections
- aviation regulations and procedures
- aircraft and avionics certification
- air traffic control personnel, procedures, and technical infrastructure

Many existing practices have been strongly influenced by human abilities and human interactions with technology-based systems. In order to define technological needs or identify where safety and capacity benefits could be obtained, a comprehensive and well documented understanding of the current air transportation system is necessary. This would provide a baseline for evaluating the effects of changes and developing a comprehensive model. Some documentation of various components of the present system is already available. Statistics are kept on some parameters, such as passenger seat miles, accidents, operational errors, and air traffic delays. However, these data are not comprehensive or detailed enough for a diagnosis of the dynamics of the entire system or for the identification of indicators of safety problems.

Fortunately, several new sources of information are now available to support the documentation of the system. Movement times of airline aircraft (in and out of gates, off of and onto runways) are regularly transmitted by satellite-based datalinks. Flight progress and flight planning data are recorded by the FAA's enhanced traffic management system. Weather data are routinely archived and can be compared with aircraft track data. Programs to monitor flight data routinely (quick access recorders) are beginning to be implemented. Air traffic control (ATC) track and communications data can be recovered and played back by diagnostic systems. The FAA is developing tools, such as the consolidated delay and analysis system, that can merge these data into a single picture of the air transportation system, which could document how the current system performs and responds to change.

A complete picture of the current air transportation system will also include economic and sociopolitical data. For example, the acceptance of a new display screen for air traffic controllers may be influenced by the perceived impact of this new technology on the overall size of their workforce. Technology upgrades to air transports that would improve the overall efficiency of the air traffic control system will only be voluntarily adopted if the economic benefits are apparent to the airlines. Technology that increases throughput in a congested terminal area may not be enthusiastically received by residents in the area who are already concerned about aircraft noise. This kind of information may be difficult to obtain, but it must be included in the comprehensive documentation of the current system.

Evaluation of Current Assumptions

The basis, goals, and assumptions that underlie current operational regulations, procedures, and certification criteria should be carefully evaluated. For example, one of the fundamental limitations of current operational capacity is runway occupancy time because existing procedures at commercial airports allow only one aircraft to be on a runway at a time. However, joint runway occupancy is common for military aircraft, which often land in formation, and is also allowed in some cases for general aviation aircraft.[2] These examples are not sufficient reason to allow joint runway occupancy or formation landings for commercial air carriers, but they do call current assumptions into question. A thorough review of the key assumptions underlying all aviation regulations and operating procedures should be undertaken in close collaboration with the FAA and industry.

Tolerable Risk Levels for Component Technologies

The lack of consistent, comprehensive, usable safety assessment methodologies has led to nonuniform, sometimes irrational, allocations of risk. For example, if the base level of risk in a safety-critical system is not known and the impact of the failure of a specific component is unclear, very high levels of integrity, such as one failure in 10^9 operations, are often assigned as a conservative strategy. In many cases, these levels cannot be definitively demonstrated, which makes it difficult to estimate the actual risk or to incorporate new technologies. Conversely, much higher levels of risk may be tacitly accepted for nontechnological components (human or procedural) of the system or for existing technological components. This approach to the risk management of component technologies can have undesirable consequences because it can deter improvements, such

---

[2] Modified air traffic control procedures that allow more than one aircraft on a runway at a time are used at the annual Experimental Aircraft Association meeting in Oshkosh, Wisconsin.

as the incorporation of new technologies, that might improve the safety of the overall system. Fundamental research that focuses on estimates of infrequent events should be conducted to improve risk assessments and estimates of the safety impacts of proposed improvements or changes in elements of the system. In addition, new methods for subcomponent risk assessment, including computer-aided design tools, would support consistent risk allocation decisions.

Development of Fundamental and Integrated Models

Once better documentation, an evaluation of current procedural assumptions, and a better assessment of tolerable risk are available, fundamental models of the air transportation system should be developed to simulate key system elements and their interdependencies. Once these fundamental models are in place, they can be integrated into total system-level models and simulations. Proposed technological and procedural changes can then be evaluated in the context of the entire air transportation system. These integrated models and simulations should include an explicit understanding of, and accounting for, the uncertainties in each fundamental model. They should also include human-in-the-loop and fast-time simulation techniques.

The development of comprehensive models on this scale will require research on the capabilities and limitations of highly complex interacting models. For example, all models include some assumptions and approximations, which are typically valid for the initial use of the model. Successful models are often subsequently modified for a new purpose or integrated with other models. After several evolutionary cycles, the original underlying assumptions often become obscured, creating a risk that the model may be misapplied. Error propagation and uncertainty management in highly complex models are important areas for additional research. In many cases, uncertainties in the elements of a high resolution model combine to make it less accurate than a relatively simple model that captures only the essential behavior of a system.

Perhaps the most challenging issue for modeling the air transportation system is the simulation of human behavior in this complex system. Currently, human-in-the-loop simulations are only used for exploration and validation because of high costs and the variability of human responses. Cost-effective methods of modeling the full range of human responses have yet to be developed. Finally, methods of validating complex models with hundreds, or even thousands, of internal parameters and only a finite amount of observable data must also be developed.

Finding. The development of models to predict the impact of technological and procedural changes on the air transportation system will be critical to the long-term future of aeronautics and to meeting NASA's goals relevant to system capacity, environmental compatibility, safety, and cost. These models could be used to identify and address barriers to the incorporation of existing and new technologies into the air transportation system.

The development of these models would require cooperation among NASA, the FAA, and the aviation industry.

UPWARDLY COMPATIBLE AEROSPACE INFORMATION SYSTEMS

Upwardly compatible aerospace information systems will be crucial to meeting many NASA goals because information technology is increasingly being used for flight control systems, propulsion control systems, and in the control of many other aircraft systems and subsystems. Better control can lead to reductions in aircraft engine emissions and aircraft noise. Upgradable information technology-based control systems could be instrumental in improving safety, reducing operating costs, and possibly increasing system throughput. Finally, new general aviation aircraft to meet NASA's goals for revitalization of this industry sector will be information-technology intensive. Therefore, they too would benefit from upwardly compatible aerospace information systems.

Current Upgrade Limitations and Difficulties

Upgrading existing air vehicles and ATM systems with new technology is usually complicated and costly because all changes must meet physical, logical, and operational redesign and recertification specifications. Because of the high cost of designing and manufacturing new air vehicles, individual aircraft in the existing air transport fleet may have service lifetimes of 40 years or longer. For information-based aircraft subsystems, 40 years represents many hardware/software obsolescence cycles and imposes severe opportunity costs in the functionality of these systems.

Equipping the existing fleet of commercial transport aircraft with GPS receivers is an excellent example of the difficulties of replacing older information-based systems with newer ones. In older narrow-body jets, such as the Boeing 727 and the Douglas-designed DC-9, a lack of physical space on the flight deck makes the installation of GPS hardware difficult or impossible. In newer wide-body aircraft where "glass flight decks" offer greater flexibility (such as the Boeing 767), software issues, interoperability with other existing systems, and the lack of well defined requirements have slowed the installation of GPS receivers. In addition, airline concerns over training costs and investment recovery have slowed the upgrade process.

These difficulties are not limited to the information systems used on aircraft. In ATM systems, the rate of technology upgrades has been even slower. The incorporation of new functionality has been limited by the very high cost of rewriting software, by the limitations of existing hardware platforms, and by the unwillingness of operators to change operating procedures.

Designing for Evolutionary Upgrades in Information Technology

Given the expected long lifetimes of both new aircraft and supporting ground systems, new approaches to software design should be created that could help minimize the cost and certification burden of inevitable software upgrades and improvements. A flexible development environment, in which the impact of new changes can be accurately assessed before production, will require new approaches and tools for designing upgrades with only the intended functionality. In the face of the increasing importance of software, perhaps the most important goal is the control of complexity. Although modular design and software architectures may seem commonplace in software development, they are essential to evolutionary changes in avionics software.

Modular Design

Modularity, which is common to most software development today, is essential to upgrading complex systems. While the basis for modularization can have several expressions, as in object clustering or methods clustering in an object-oriented design, it is important that modules be aligned with critical system and subsystem functionality. This alignment helps limit unintended interactions (the bane of system upgrading) and makes interfaces more constant. Functional modularity, then, is an appropriate feature of air vehicle avionics systems.

In general, modularity is important to software and information system design for several reasons. First, modular software is usually easier to specify and certify than nonmodular software. Second, modules are easier to change or upgrade, especially if interfaces with the overall system do not change. Third, a modular system designed for expansion can be much more receptive to new functionality, provided that modules have been well defined along functional lines. This alignment, or functional partitioning, is critical for ensuring that modular systems or their upgrades work as intended. Ignoring this alignment will not decrease unintended interactions and may even increase complexity. Abstraction is another important benefit of functional partitioning. In applications such as avionics, well-defined abstractions based on good functional partitioning, can be used to manage system complexity. However, complex systems interactions are sometimes hidden. Therefore, new tools are needed to measure and improve complex systems interactions.

Hardware and software interfaces are closely related to modularity. Explicit interfaces that have a high likelihood of being invariant to evolutionary change is an attribute of well-defined modularity. Good examples can be found in digital networking, where scores of improvements have been made over the past 15 years without material changes to the underlying protocols. Interfaces should be designed to occur at points where changes are likely to be minimal, rather than at points that offer programming convenience. Tools to help identify these invariant points and to reveal inconsistencies introduced into software systems through changes in underlying hardware need to be developed.

The Defense Advanced Research Projects Agency's existing research project on the evolutionary design of complex systems is a recent attempt to build evolvable software. The approaches under investigation in this program for ground-based information systems and a small number of military air vehicles might also be applicable to the development of software used on board commercial transport aircraft, general aviation aircraft, and the ground-based portions of ATM and communications/navigation/surveillance (CNS) systems.

Platform independence is another software characteristic that helps information systems evolve. Although UNIX™ has demonstrated a good deal of versatility, the notion of a Java virtual machine is perhaps the most well known, current example of software that will run on almost any machine.[3] Java is a language that is just emerging, however, and still lacks many of the required attributes for safety-critical applications.

Software Architectures

Software architectures have emerged as the leading conceptual framework for organizing software development processes and products.[4] Because they can employ multiple levels of abstraction to help manage complexity, they are well suited for the design and evolution of large or complex systems. Though very flexible in its inherent elements, an architecture may have many of the same attributes of modularity mentioned above. Well formulated architectures permit a high level of functionality such as a flight control command like "maintain present altitude" to first be defined and then mapped to lower, more detailed implementation levels using rigorous methods. These methods can be based on mathematical logic and, therefore, lend themselves to digitally defined systems. However, their extension to nonlogic-based systems, such as the analog components found in aircraft control systems, are just now being investigated.

Software architectures can facilitate the design of upwardly compatible systems in two ways. First, the high level of abstraction helps bridge the gap between requirements and implementations, thus linking models and systems. Second, future changes can be made at any level of abstraction and, if they are architecturally consistent, changes can be shown to be functionally compatible; in other words, they perform the specified function and do not perform other specified functions. Unfortunately, unintended or unanticipated effects cannot yet be ruled out.

Finding. The expected long lifetimes of current and future aircraft and ATM systems will necessitate a number of upgrades to their information-based components. To reduce the

[3] UNIX is a computer operating system that can be used by almost any computer architecture. The UNIX operating system was the basis for most of the initial hosts and servers on the Internet. JAVA, a computer language widely used by internet programmers, allows programs, commands, and functions on a web site to be executed on any computer that accesses the site.

[4] Software architecture, in its simplest terms, is the structure of components and their interrelationships. As an approach to system design, it is usually considered structural rather than functional, but in avionics, structure and function should be aligned.

cost of upgrades that involve new technology or additional functionality, aerospace information systems must be designed to be upwardly compatible. This can be accomplished by developing software that is adaptable, functionally modular, employs an open architecture, and uses well defined interfaces that are unlikely to change. The ability to upgrade information technology-based control systems can contribute to achieving NASA's goals for general aviation, improved safety, reduced operating costs, and increased system throughput.

METHODOLOGIES FOR THE DEVELOPMENT OF HIGH INTEGRITY SOFTWARE

The functionality of nearly all future aerospace systems will be governed by software. In fact, aircraft flight control systems, engine combustion control systems, landing systems, CNS systems, and ATC systems are already heavily dependent on software. Despite this, the process by which aircraft manufacturers and the airline industry develop software, and the FAA's procedures for certification, are still evolving, as evidenced by a recent call from the FAA administrator for a review of aircraft and avionics software certification processes by the RTCA.[5]

Improvements in methods to develop and certify software used in aircraft and ATM systems will have an impact on meeting many of NASA's goals. Improved software development methods are expected to improve safety (as well as the ability to demonstrate levels of safety) and increase system throughput. Improved software certification will also reduce aircraft costs and the time it takes to deploy new or modified aircraft. Because many of the new general aviation aircraft designed to meet NASA's goal for revitalization of the industry will be software dependent, breakthroughs in software development will be key.

Developing, Ensuring, and Maintaining High Integrity Software

Most aerospace systems are safety critical, operate in near real time, respond to constantly changing environments, and involve significant human interaction. As a consequence, aerospace software has higher V&V requirements than software used for many other applications. Thus, the costs of software development, maintenance, and upgrading have been high.

As aerospace software becomes even more complex and the number of lines of code for a given system exceeds one million,[6] present development techniques and V&V practices that rely on structured programming techniques, on well defined data structures and typing of variables, and on exhaustive testing will not be adequate to ensure safety-critical

[5] Personal communication from FAA Administrator Jane Garvey to David S. Watrous, President, RTCA, February 11, 1998. This letter can be viewed on the RTCA World Wide Web site: http://www.rtca.org/CTF/faa_tasking.htm.

[6] For example, the 1,300 embedded computers onboard the Boeing 777 contain a total of 4 million lines of code (Deyst, 1997).

operation. Validation of software through these techniques is generally limited by the amount that developers are willing to spend, and result in reliability estimates on the order of 10^{-4} failures per hour of operation (Littlewood and Strigini, 1993). Though likely unverifiable, values on the order of 10^{-9} are mandated for civil aviation (Deyst, 1997). Therefore, breakthrough software engineering methodologies are needed to enable the development, validation, verification, assessment, and maintenance of high integrity software used for aerospace systems.

One potential approach is the use of mathematically-based formal methods that enable software designers to predict the behavior of a software system by building mathematical models, just as civil engineers construct mathematical models of bridges. Formal logic provides rules that enable valid conclusions to be drawn from explicit, valid premises or statements about the world. Manipulations of the rules are called proofs. Formal methods, then, consist of specifications about the world, the requirements of a system, and the verification methods that can be used to produce the proof.

Once the operating environment for a given software application is well known and important failure modes have been identified, the necessary requirements can be stated. Formal methods can then help ensure the development of a system that meets functional and safety requirements, identify holes in a software system's design, and avoid, remove, and tolerate faults.

Areas where formal methods can make a contribution include:

- validation of requirements—model building and model checking to determine the validity of system components, including consistency with the stated expectations of human operators
- software specification—capturing and describing well designed and functionally accurate abstractions to control complexity
- software derivation—methodologies and tools that can produce code automatically from a specification language
- software analysis and verification—validating specifications and verifying that implemented software meets requirements
- software safety certification—demonstrating that software will operate safely and as intended when embedded in the aircraft

A key issue in the development of formal methods and other sophisticated V&V techniques is the requirement that they be usable by designated engineering representatives of the FAA or other certification authority. If the tools and artifacts of formal methods are too complex or esoteric, they will not be fully understood and will not accomplish the safety or certification objectives.

Though formal methods have held the potential for building critical software systems for some time, their utility for large systems is still elusive. The functionality of software must be specified so that it faithfully represents a model that itself must have been validated by some means. As mentioned above, new affordable methods must be found that both verify intended functions and reveal the unintended relationships in an avionics system, modularly designed or not. These software development methods could significantly reduce the software-related design and maintenance costs of aerospace systems and should improve safety through better system definition. Reduced software development costs could also facilitate the migration of advanced information systems into the general aviation fleet. Appropriate methodologies may emerge from nonaerospace applications, but commercially available tools will probably not be applicable to aerospace software given its size and complexity, and potential liability issues. Thus, NASA, the FAA, aerospace manufacturers, and the airline industry will have to pursue formal methods for software development aggressively.

Software Certification

For a number of years, software certification standards and processes have addressed certification at the system level rather than the software level. This mitigates the unfeasibility of showing that the software is ultra reliable. Dependability assessment techniques that can arrive at overall quantified judgments about the trustworthiness of software by combining disparate sources of evidence (such as formal proof, test data, and engineering judgment) are urgently needed. Safety arguments, systematically presented in the form of a safety case document, are also needed. These techniques would provide the aircraft industry with an approach to certification that is rapid, repeatable, and accurate.

Finding. New software engineering methodologies could facilitate the development, validation, verification, and maintenance of high integrity software. These methodologies include: formal specification methods, including verifiable high-level languages; formal methods of validating specifications and consequent software; techniques for building and checking models to determine the validity of system components, methods of combining disparate sources of software certification evidence; documentation of safety arguments in the form of safety cases; and models of human operators and their roles and expectations. These approaches to software development address NASA's air transportation goals related to improved safety, increased throughput, and a revitalized general aviation industry. Improved software certification would also reduce aircraft costs and design time.

ADVANCED HUMAN-AUTOMATION SYSTEMS

Despite the fact that information technology and automation have improved the safety and efficiency of both aircraft and the ground systems that support them, human operators are still occasionally placed in difficult and stressful situations that lead to mistakes. For example, crew error has been the leading cause of aircraft accidents for a number of years, as shown in Figure 4-1. In accidents involving commercial air carriers, approximately 45 percent of the crew-related accidents are due to controlled-flight-into-terrain[7]. As humans become the limiting element in the critical systems of air transportation, automation must be used to support critical human performance. For example, the recently adopted enhanced ground proximity warning system automatically alerts pilots to unsafe conditions and supports the decision-making process by providing a graphical representation of terrain. However, as machines become more and more capable, assumptions about which tasks should be left to humans and which tasks should be automated will have to be continuously reappraised (see Box 4-1).

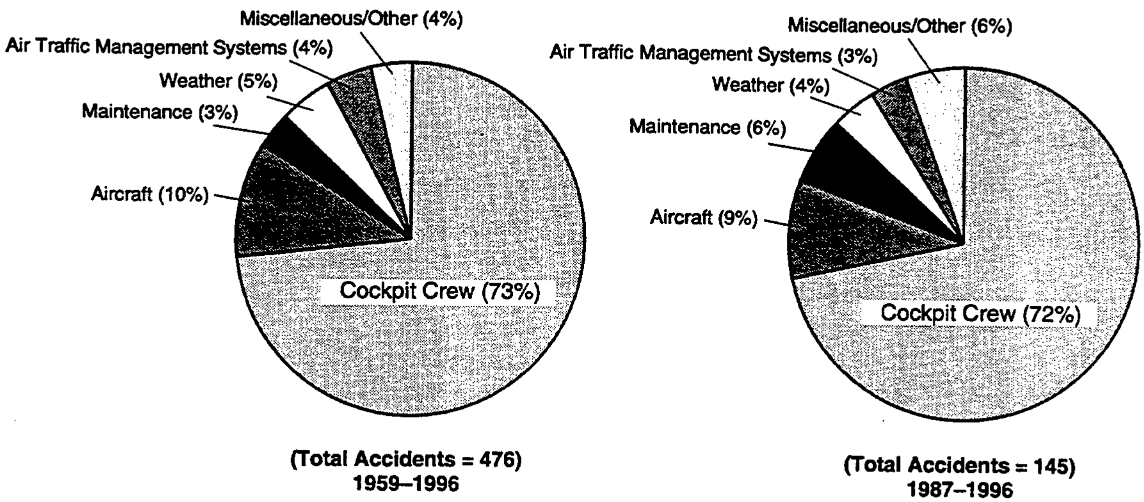


FIGURE 4-1 Primary causal factors for worldwide aircraft accidents resulting in total hull loss.

Improving Human-Computer Interaction/Integration

A key issue in the development of integrated human-automation systems is the allocation of responsibility. Humans and computer-based automation systems have complementary strengths and weakness, as shown in Box 4-1. A well integrated human machine system can perform better than either a fully automated or a fully manual system. However, the current state of integration is still immature. Some general design principles have been established (e.g., humans are poor task monitors), but a systematic methodology for evaluating new systems has not been developed.

Many irrational judgments have been made about which tasks humans should perform and which tasks machines should perform. To improve the design of human-automation systems, all tasks must be examined collectively. Unfortunately, researchers in human factors tend to focus on the human-machine interface for complicated systems, such as highly computerized aircraft flight decks, from the computer display to the human

[7] Personal communication from Mike Tracy, Airplane Safety Engineering Group, The Boeing Company, August 20, 1998.

perspective; while information scientists tend to focus on the computer processor-display interface.

More attention is finally being paid to the unique role of human cognition in the operation of human-automation systems. The design strategies based on this awareness are often referred to as cognitive engineering or human-centered design, which seeks to define system functionality based on how the operator thinks about a task rather than on how the design engineer thinks about the automation system. A broad focus and systems perspective is now needed that combines each of these approaches to studying the human and the machine. NASA's efforts in this area of research should be teamed with other government agencies with an interest in studying human factors, information systems, and the cognitive sciences, such as the National Science Foundation (NSF), the National Institutes of Health (NIH), and the Department of Defense (DOD).

BOX 4-1

The Original "Fitts" List for Designing Human-Automation Systems

Humans appear to surpass present-day machines with respect to the following:

1. Ability to detect small amounts of visual or acoustic energy
2. Ability to perceive patterns of light or sound
3. Ability to improvise and use flexible procedures
4. Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time
5. Ability to reason exclusively
6. Ability to exercise judgment

Present-day machines appear to surpass humans with respect to the following:

1. Ability to respond quickly to control signals and to apply great force smoothly and precisely
2. Ability to perform repetitive, routine tasks
3. Ability to store information briefly and then to erase it completely
4. Ability to reason deductively, including computational ability
5. Ability to handle highly complex operations, that is, to do many different things at once

Source: Fitts, 1951.

The evaluation of new or proposed systems will be especially important. Because of the complex and apparently stochastic nature of human performance, it is extremely difficult to evaluate human-machine system performance in realistic operational settings. Traditional evaluation methods based on human-factors and experimental psychology have been limited to a few experimental variables so that direct causal effects could be identified. However, realistic operational environments (such as an aircraft flight deck or an ATC station) are extremely complex, and experimental variables are often confused with secondary causal factors. Therefore, advanced methodologies for evaluating complex human-automation systems will have to be based on advanced simulation systems, as well as sophisticated, multi-attribute methods of collecting and analyzing field data.

Improving Pilot Situation Awareness

Many of the human errors in flight operations can be attributed to the loss of situation awareness.[8] For example a pilot or controller's failure to recognize and take proper corrective action when a mechanical failure or flight hazard occurs is usually attributable to a lack of perception or an inability to recognize the consequences of an action. Lack of situation awareness can result from too little information (i.e., a lack of critical information), too much information (i.e., clutter or simple overload which can prevent a pilot or controller from internalizing critical information), or a misinterpretation of available information. In the future, the information potentially useful to a pilot's situation awareness will probably be provided from the following sources: ground proximity warning systems and digital terrain maps; wind shear and clear air turbulence sensors; collision avoidance systems; onboard weather radar; high precision guidance and navigation systems; an air-to-ground datalink; real-time satellite-based weather forecasts; air traffic control data; maintenance data; mission or company management data; onboard synthetic vision sensors; and onboard aircraft performance and status sensors.

Because the cognitive capability of human beings is limited, these data will have to be presented in a way that supports the pilot or controller's situation awareness. Therefore, the integrated-systems approach to the allocation of human and machine tasks should also be used for the development of pilot and controller interfaces. For pilots, these will include integrated alerting systems where multiple hazard sensors are integrated to provide the pilot with a coherent threat picture. Other information management tools, flight displays, and new operational procedures should also be developed to support pilot situation awareness. For controllers, the integrated human-systems approach will facilitate the development of decision aids that can help maintain situation awareness while managing the increased traffic allowed under the reduced aircraft separation standards that will be necessary to realize the NASA goal of increased throughput.

---

[8] Situation awareness is defined as the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future (Endsley and Rodgers, 1994). Situation awareness for a pilot or aircrew involves awareness of flight conditions, such as airspeed, altitude, and geographic location, and knowledge of the status of the aircraft, such as fuel level and the existence of or absence of mechanical malfunctions.

Unpiloted Commercial Transports, an Extreme Solution to Pilot Task Allocation

At the extreme end of the human-automation spectrum, the committee considered the challenges (both technical and political) and advantages of fully automated commercial transport aircraft operations. Although at first glance this might seem unrealistic, consider that the military has already identified uninhabited air vehicles (UAVs) as a key technological system for improving performance, reducing human exposure to risk, and reducing the cost of air operations. One might even consider if any of the 70 percent of air carrier accidents attributed to crew error could be avoided by autonomous operation. Conversely, one might also ask how many accidents have been avoided by human intervention.

The technology to operate air carriers automatically is already available. Most modern transport aircraft have the capability to perform fully automatic flight from takeoff to landing along a preprogrammed course. The only manual operation required by the pilots is taxiing away from the gate and rolling out after landing. However, fully unpiloted operation is not practical today because disturbances in the external operating environment, such as turbulence, winds, severe weather, traffic, and air traffic control maneuvers, often require changes to the preplanned trajectory. The main role of the pilot in today's commercial air carrier operations is to adapt to changing environments or respond to mechanical failures.[9]

The key technologies that would enable unpiloted transport operations are highly reliable, goal-level guidance and control systems and advanced flight planning algorithms. Goal-level guidance and control systems are much more automated than most current flight management systems, in which automation is instructed or programmed at the specific instruction level. Goal-level systems must be able to select a specific course of action to accomplish a high-level goal, such as the safe arrival of an aircraft at a given point in a route. System reliability and interaircraft coordination must also be addressed for highly automated flight control systems before unpiloted commercial transports will be feasible.

Although unpiloted commercial transport aircraft may never be used because of a lack of public acceptance, research and technology development focused on unpiloted operations could identify critical guidance, control, and pilot decision-making elements that should be considered in the design of flight management control systems for either piloted or unpiloted air vehicles. Since the development of unpiloted air vehicles does not truly eliminate the possibility of human error, but shifts the potential for error from the operator to the designer, the increased rigor necessary during design would also benefit both piloted or unpiloted air vehicles. Therefore, to further the goals related to air transportation safety and efficiency, NASA should consider developing prototype unpiloted civil/commercial air vehicles that leverage the results of related DOD UAV research.

---

[9] It should be noted that a great deal of skill and training is required to accomplish these tasks.

Finding. Although automation has already improved the safety and increased the efficiency of air travel, additional progress can be made through improvements in aviation-related human-automation systems, such as aircraft flight decks. Key issues that require NASA research support include human-machine task allocation and pilot situation awareness. Advances in technology for UAVs (unpiloted air vehicles) may also contribute to the fulfillment of NASA's safety and capacity goals for air transportation operations involving piloted aircraft.

PRECISION AIR TRAFFIC MANAGEMENT/AIRCRAFT OPERATIONS

Increasing capacity will be a key driver for future high performance ATM systems. An order of magnitude improvement in the precision of ATM and aircraft operations, such as a reduction in airway widths from 4 miles to 0.4 miles, could increase capacity, while simultaneously maintaining or improving safety, for oceanic, en route domestic, and terminal airspace flight operations and could lead to reductions in the cost of air travel.

Technology designed to make commercial transport aircraft operations more precise could also be applied to general aviation, provided costs can be kept low. More precise operations would enable more privately owned aircraft to operate in adverse weather conditions and high traffic areas, thus contributing to a revitalization of this aircraft market sector. Supersonic air vehicle operations could also benefit from improved ATM that would allow for shorter overland flight distances, reduced aircraft separations for transoceanic flights, and the avoidance of noise sensitive areas.

Improvements in ATM may be possible through enhanced CNS and ATM decision support tools that would enable new ATM separation standards and reduce "intervention buffers."[10] Improvements could also be enabled by building on emerging technologies used for weather detection, precise aircraft navigation and surveillance, and air-to-ground data transfer. Critical issues that must be addressed with new or existing technologies include better integration of information from a number of different algorithms, sensors, and systems; and a better understanding of human-automation issues.

Air-to-Ground Datalinks for Precise Controller-to-Pilot Communications

The fast pace and high pressure of a busy airport or air traffic control center necessitates abbreviated interchanges on the voice channels used to control aircraft movements. Very often these commands are safety critical, that is, if they are misinterpreted or missed altogether, serious consequences can result. Although no breakthrough would be necessary to make communications more reliable, the introduction of more modern, verifiable digital technology is imperative. The challenge is to provide reliable communications with the

[10] An intervention buffer is the normal minimum spacing between aircraft that, if not maintained, will compel an air traffic controller to direct course corrections.

pilot without obscuring the normal voice interactions that must continue, if for no other reason than to handle unanticipated occurrences.

Although datalink communications to aircraft have been technically feasible for a number of years, their use has been limited mostly to private intra-airline communications providers, such as ARINC, which transmit airline operational information, weather, air terminal information system (ATIS) and some ATC clearances in text format. Broader implementation of digital data communications and graphical datalinks have been limited primarily by difficulties in developing ATC automation tools. Datalinks could allow direct exchanges of data between onboard computers, as well as between aircraft and ground computers, which would improve coordination of aircraft, especially closely spaced parallel approaches, minimal noise approaches and departure procedures, and very close (i.e., near formation) operations, which would be necessary to achieve the NASA capacity goal of increased capacity.

Improved Weather Detection Sensors

Sensors that could "see" adverse weather conditions, including clear air turbulence and icing regions, and provide early warning to the pilot would permit the planning and execution of avoidance maneuvers better than present radar systems. Current airborne weather radars only sense precipitation (some systems can also detect turbulence in the precipitation) through Doppler velocity measurements. Other sensors, such as lightning detectors, also indicate regions of high convective activity and hence the potential for convective turbulence. Clear air turbulence and icing are the key weather hazards for which there are no reliable methods of remote detection. Currently, the most commonly available indicators of these hazards are pilot reports from other aircraft. In addition to sensors, pilots need methods and systems that can integrate all available weather information (from sensors, pilot reports, forecasts, and numerical models).

Precision Navigation and Surveillance

The precise determination of the flight trajectory of one's own aircraft and all other aircraft in proximity to it could have an impact on meeting several of NASA's air transportation goals. For example, more precise flight tracks could potentially lead to reduced flight times because aircraft could operate in closer proximity to each other without conflict. Small reductions in flight time could reduce overall fuel consumption enough to create large cost savings for large air carriers. Less flight time for numerous individual aircraft could also lead to large aggregate reductions in overall aircraft noise and emissions. These capabilities are consistent with the FAA's concept of "free flight," an attempt to move the U.S. national airspace system from a centralized command-and-control system between pilots and air traffic controllers to a distributed system that allows pilots, whenever practical, to choose their own routes and file flight plans that follow the most efficient and economical routes.

The technology to determine precise flight trajectories and distribute these trajectories to all nearby aircraft is already in hand. Satellite navigation based on GPS and combined with other sensors, such as inertial navigation units, can provide very precise three-dimensional positioning, velocity, and time. ADS can be used to broadcast this information for one aircraft to all other ADS-equipped aircraft. Although these systems have not been widely adopted due to inertia in the air transportation system as discussed early in the chapter, long-term NASA research and technology development focused on precise navigation and surveillance is not likely to speed their implementation.

Fully Autonomous Air Traffic Operations

"Free flight" promises to further NASA's safety and efficiency goals, but the concept does not completely free aircraft from reliance on ground-based air traffic control infrastructures, especially in terminal areas. Free flight would actually limit pilot flexibility in certain situations, for example, to ensure aircraft separation at high-traffic airports and in congested airspace (Free Flight, 1998), to prevent unauthorized entry into special use airspace, and for other safety reasons. However, if pilot task allocation and situation awareness could be optimized, and the precise location of everything that might concern a pilot, including the location of the ground, could be made available in all weather and flight conditions, the safe operation of fully autonomous aircraft might be possible.

Imagine a flight deck "heads-up display" that shows an outline of the terrain ahead consistent with the altitude and orientation of the aircraft, the location of all aircraft ahead—as well as above, below, and beside—and their predicted trajectories, and a "rear-view mirror" analog view behind the aircraft, all in their correct locations relative to the aircraft. This type of display would require that precise navigation and surveillance technologies be combined with enhanced weather sensors, sensors that provide visual imagery in all light and weather conditions, and databases on digital terrain and man-made obstacles. Many of these component technologies already exist or are close to realization, but integrating them into a system optimized for human-machine task allocation and pilot situation awareness would represent a major breakthrough.

Fully autonomous air traffic control capability that is independent of ground-based infrastructure offers many possibilities for changes in the way the air transportation system operates that would have a positive impact on meeting NASA's goals related to air transportation cost, safety, noise and emissions, and possibly throughput. In addition to free flight during the enroute phase of a flight, all airports, both high and low density, public and private, could have defined approach glide paths that are direction-of-arrival dependent and weather-dependent. These approaches could be flown in any light and visibility conditions without interactions with control towers. These capabilities would have obvious benefits for less-developed countries and for operations in remote or austere environments, where the existence of ground-based infrastructures other than a safe landing area would no longer be required.

In order to ensure the widespread use of aircraft-based ATC systems by commercial, military, and general aviation aircraft, cost must be carefully considered during their development. Total autonomy from all ground-based infrastructure in a given region would be impossible unless all aircraft use aircraft-based ATC systems.

Finding. Precision ATM and aircraft operations will be important to meeting NASA's goals related to air transportation cost, safety, noise and emissions, throughput, high-speed air travel, and general aviation. In the near term, precision ATM will probably be based on emerging technologies now used for weather detection, precise navigation and surveillance, and air-to-ground data transfer and communications. However, achieving NASA's goals in the long term will require the development and implementation of an aircraft-based ATC capability that is totally independent of ground-based infrastructures.

MITIGATING CONSTRAINTS IN TERMINAL AREAS

New technologies and procedures that increase throughput in terminal environments will be essential to growth in the air transportation system and to achieving NASA's goal to triple the aviation system throughput. The economics of airline operations create a demand for increased frequency of service because this is highly valued by consumers. The national air transportation system throughput is fundamentally limited in terminal environments by two major barriers: (1) runaway occupancy time, the primary constraint under visual flight rules, and (2) wake vortex limitations on aircraft separation under instrument flight rules. Because these barriers are not likely to be mitigated through the construction of new airports, a wide range of candidate improvements in aircraft, airport and/or ATM technology, as well as the integration of new vehicle types into the scheduled passenger transportation system at the most congested airports, should be evaluated. New technologies and procedures would maximize the productivity of existing infrastructure while maintaining the high level of safety associated with scheduled passenger transportation. Mitigating the constraints in terminal environments would also lessen the pressure to expand existing airports.

Reducing terminal-area constraints would also further several of NASA's goals in addition to throughput. By allowing aircraft to operate more freely and with less delay in terminal areas, engine emissions and aircraft noise would be reduced. Costly takeoff and landing delays would also be reduced for commercial air carriers, enabling a potential reduction in air travel costs. Technology developments focused on reducing terminal constraints, such as methods to mitigate wake vortices, could also contribute to improved safety and an improved operating environment for general aviation.

Reduced Runway Occupancy Time

Current FAA/NASA programs are attempting to increase throughput at airports through a range of initiatives including simultaneous independent operations on more closely spaced parallel runways and more efficient use of terminal airspace. For operation under visual flight rules, the throughput (the number of operations that can be accommodated) for a single runway is regulated by the amount of time it takes an aircraft to proceed from threshold crossing to a runway exit. Present ATC operating rules do not permit two aircraft to be on the same runway at the same time, which suggests that strategies that could reduce runway occupancy time could increase capacity and throughput. If more than one aircraft could safely occupy the same runway, runway occupancy time would be effectively reduced.

Reduction in Aircraft Velocity on Roll out

Once an aircraft touches down, its landing speed, combined with braking and thrust reversers, determines how long it takes for the aircraft to slow down enough to turn off the runway. Deceleration rates also depend on runway surface conditions, such as wet or dry pavement. New runway materials that reduce the time required to slow the aircraft would shorten runway occupancy time. Onboard technologies, such as actively controlled braking systems or braking guidance systems, may increase deceleration profiles and enable high-speed exits. Finally, vertical/short takeoff and landing (V/STOL) aircraft land at relatively slow speeds (or even zero forward velocity) and have lower runway occupancy times than conventional aircraft. If V/STOL aircraft could be sequenced onto existing airport runways very precisely, and apart from the arrival stream of other air traffic, runway occupancy time per operation would be reduced.

Wide Runways/Formation Landings

Today, aircraft operate simultaneously on intersecting runways under the "land-and hold-short" concept.[11] In theory, two aircraft could land at different touchdown points on the same runway, either in parallel operations on wide runways or in-trail operations on long runways. This formation landing, enabled by advanced flight control systems, aircraft-to-aircraft surveillance systems, and pilot-controller decision aids, would effectively increase the capacity of existing runways (or runways with relatively modest modifications).[12] Ideally, this capability would be available for visual flight and instrument flight operations.

[11] Land-and-hold-short procedures allow an aircraft to approach an intersecting runway with active traffic as long as the pilot accepts the responsibility for ensuring sufficient stopping distance before the aircraft reaches the intersection point.

[12] These proposed formation procedures would not place aircraft in wingtip-to-wingtip proximity, as is the case for formation procedures used by military fighters. The aircraft separation envisioned would be similar to the landing spacing used for military transports.

The required technologies entail very precise control of aircraft positions in all four dimensions, including velocity, by precise position tracking by air traffic control with very rapid updates for aircraft position and intent. Flight crews would require rapid updates of position and intent for all nearby aircraft. Onboard collision-avoidance systems would also have to be more highly automated than current systems so pilots could take rapid evasive action, if necessary.

Mitigation of Wake Vortices

Wake turbulence created by vortices emanating from aircraft wings is one of the major constraints on the overall throughput capacity of the air transportation system. Wake turbulence limits enroute in-trail spacing, takeoff and landing spacing, and airport runway spacing. Airports that do have closely-spaced parallel runways (less than 4,300 feet apart) cannot use them for simultaneous, independent operations because of the safety implications of wakes drifting across the runways. Recent increases in separation requirements to compensate for wake turbulence from the heaviest commercial transports has limited capacity at some airports even more.

Efforts are being made to develop sensor systems to detect and measure wing vortices. Other approaches to mitigating the effects of wake turbulence include source alleviation and encounter management techniques. Source alleviation methods, which reduce or control vortices, would also allow closer spacing of aircraft on approach. Either the energy created by the vortices would be extracted or the wing would be redesigned to reduce or eliminate vortices at the source. The development of techniques to safely "manage" wake vortices may involve changes in procedural approaches, such as displaced thresholds, variable glide path approaches, precision approach paths for all-weather operations, and dynamic encounter aids associated with advanced sensors. Progress in any of these areas could have significant benefits in terms of safety and throughput.

Vertical/Short Takeoff and Landing Aircraft to Enhance Capacity

Another approach to increasing the capacity of terminal areas is use of V/STOL aircraft, including advanced civil tilt-rotor designs. NASA studied the economic viability of V/STOL aircraft in the late 1970s, and their use appeared to be feasible even though new air vehicles and the associated infrastructure, such as vertiports, would have to be developed. V/STOL aircraft could serve the shorter-distance markets cost effectively if they could operate out of existing airports. If they did not affect the capacity available for conventional runway operations, they would represent new net capacity. [13]

---

[13] High-speed rail is often suggested as a substitute for short-haul air transport. However, the economic viability of high speed rail does not make it an attractive alternative in most U.S. intercity travel markets.

A concept known as simultaneous noninterfering operations, currently being investigated by Boeing Helicopters and NASA Ames Research Center, could potentially allow V/STOL aircraft to operate out of existing airports without interfering with existing commercial jet traffic. Improvements in ATC and aircraft operations could make this concept operationally viable. Technology development for V/STOL aircraft, such as tilt-rotors, would have to be increased and accelerated to develop economical, reliable, and safe V/STOL aircraft. The variable-diameter tilt-rotor concept has an extended prop-rotor diameter during hover and low-speed flight and a retracted prop-rotor diameter during high-speed cruise operation (Rosen, 1997). This capability would dramatically improve vertical takeoff payload fractions and propulsive cruise efficiencies in forward flight. Other important technological improvements applicable to all air vehicles, such as improved propulsion systems and improved structures and materials, are discussed in Chapter 3.

Personal Air Travel

A potential area of breakthrough technology that could meet NASA's throughput goal in the long term without extensive technology upgrades to existing airports or the construction of new public airports would be the design and deployment of personal air transportation vehicles that could offer "door-to-door" transportation under all weather conditions. If personal vehicles could be operated safely without extensive pilot training, they could revolutionize the mobility of the population. The performance level of a personal air transportation system vehicle would have to be much higher than the performance level of existing general aviation vehicles. Personal transportation aircraft will need to have V/STOL capability and will need to operate using the existing ground-transportation infrastructure (i.e., roads and highways). This could make on-demand, door-to-door transportation possible, which would avoid the time and cost of accessing existing airports and accommodating scheduled airline flights.[14]

In addition to V/STOL vehicle technology, a number of advances in information technology would be necessary for safe and efficient personal air transportation systems. Many of these technologies have been described in this chapter, including advances in vehicle guidance and control systems, weather sensors, onboard precise navigation and surveillance systems, and collision avoidance and flight management systems that are affordable for small aircraft. The research and technology development for unpiloted commercial air transports, based on advances in UAV development, and fully autonomous aircraft-based ATC would have to be applied to personal air vehicles with built-in system redundancy, simplicity, and low cost. In addition, the impact of large numbers of private vehicles on the safety of the existing air transportation system would have to be determined, which would depend on the improved modeling capabilities described earlier.

[14] For more details about one concept to enable these capabilities, known as the VTOL-Converticar, see Bushnell, 1998.

In the most extreme and optimistic scenario, personal aircraft that are virtually unconstrained in terminal areas could support long-distance commuting, provide access to rural and "inaccessible" areas, and could even "unclog" some densely populated areas in the United States and abroad.

Finding. Increasing air transportation system throughput depends directly on reducing constraints in terminal areas. Technology developments in this area should focus on reducing runway occupancy time, mitigating the effects of aircraft wake vortices, and enabling V/STOL aircraft to operate from existing airports and runways without reducing capacity available for other air traffic. To the extent that these improvements can provide more precise control of aircraft operations or can reduce the potentially harmful effects of wake vortices, they could also improve aviation safety and operating conditions for general aviation aircraft. In the long term, personal air transportation vehicles could be a breakthrough that would achieve NASA's throughput goal by allowing millions of air travelers to bypass existing airports and air travel infrastructures. If these vehicles were produced and sold by general aviation manufacturers, NASA's goal of revitalizing this industry could also be met.

REFERENCES

Bushnell, D.M. 1998. Frontiers of the "Responsibly Imaginable" in (Civilian) Aeronautics, AIAA paper 98-0001. Reston, Virginia: American Institute of Aeronautics and Astronautics.

Deyst, J.J. 1997. Aerospace Information Systems. Presentation to the Committee to Identify Potential Breakthrough Technologies and Assess Long-term R&D Goals in Aeronautics and Space Transportation Technology, Cambridge, Massachusetts, November 18, 1997.

Endsley, M.R. and M.D. Rodgers. 1994. Situation Awareness Information Requirements for En Route Air Traffic Control, Final Report. DOT/FAA/AM-94/27. Washington, D.C.: Federal Aviation Administration.

Fitts, P.M. 1951. Human Engineering for an Effective Air Navigation and Traffic Control System. Washington, D.C.: National Research Council.

Free Flight. 1998. FAA Free Flight World Wide Web site, www.faa.gov/freeflight

Littlewood, B. and L. Strigini. 1993. Validation of Ultrahigh Dependability for Software-Based Systems. Communications of the ACM, 36(11).

Rosen, K. M. 1997. Memo to the Committee to Identify Potential Breakthrough Technologies and Assess Long-term R&D Goals in Aeronautics and Space Transportation Technology, United Technologies, Sikorsky Aircraft, November 5, 1997.

5

Space Transportation Technology

INTRODUCTION

NASA's third pillar for success in aeronautics and space transportation technology addresses access to space and recognizes that low-cost access is the key to exploiting the commercial potential of space, as well as the key to expanding space research and exploration. Two technology goals are listed under Pillar Three that would extend the spacefaring capability of the United States and enable activities in space that are only talked about today. The two goals are as follows:

> **Goal 9**: Reduce the payload cost to low-Earth orbit by an order of magnitude, from $10,000 to $1,000 per pound, within 10 years.
>
> **Goal 10:** Reduce the payload cost to low-Earth orbit by an additional order of magnitude, from $1,000's to $100's per pound by 2020.

While attempting to identify potential breakthrough technologies that could achieve these NASA goals, the committee noted that both goals focus only on achieving low-Earth orbit (LEO). However, this is only one aspect of the space transportation problem. Most satellites that are launched into Earth orbit, even if it is LEO, require some form of upper stage propulsion or orbital transfer vehicle to boost the satellite into an operational orbit.[1] In addition, space vehicles used for scientific exploration must often travel beyond Earth's orbit into deep space. Providing this additional transport will be expensive and will add considerably to the costs of space missions. Thus, the committee suggests that NASA consider modifying the existing goals or adding additional goals to provide "stretch challenges" for:

- reducing the overall cost of space transportation, including the launch stage and the final propulsive stage used in orbital transfer
- minimizing the cost of developing far-reaching space transportation technologies that enable new deep-space missions

---

[1] From January 1, 1988, to January 1, 1998, launched operational payloads (not including rocket stages or debris) reached the following operational orbits: low-Earth orbit (less than 2,000 km): 793 satellites; high-Earth orbit (more than 2,000 km): 422 satellites; deep-space probes beyond Earth orbit: 16; military satellites with no unclassified orbital data: 65; total operational spacecraft launched: 1,296. (Devere, 1998)

NASA's current space transportation goals reflect the belief that customers will require much less expensive, more reliable, and more flexible launch services than are available today. The major cost drivers for today's expendable or reusable launch systems are listed below:

- amortization of large development costs
- complex operations: vehicle assembly, checkout of numerous complex interfaces, and launch command and control
- maintenance, monitoring, and perpetual improvements in hardware designed for performance, not robustness
- limited reuse of hardware
- low launch rates

Estimates of the approximate cost per pound to orbit for several U.S. expendable launch vehicles are shown in Table 5-1.

Table 5-1 Approximate Cost per Pound for Major U.S. Launch Vehicles

Vehicle	Cost Per Pound	
	Low Earth Orbit	Geosynchronous Earth Orbit
Delta II	$4,500	$25,000
Atlas IIA	$5,800	$29,000
Titan III	$5,000	$28,000
Titan IV-SRMU (no upper stage)	$4,600	—
Centaur (with upper stage)	—	$26,000

Source: Dawson, 1994.

The committee believes that the low-cost attributes of future launch systems will be simplified launch operations, robust design and operating margins, and near complete reuse of hardware. Large design and operating margins will insure long life and minimum checkout and maintenance costs. Complete or near-complete reuse of hardware will keep replacement costs low. Thus, the most viable way to achieve the NASA goals for low-cost access to space is to develop robust, highly reusable launch vehicles (RLVs) with aircraft-like maintenance and frequency of operation. The potential enabling technologies identified by the committee are discussed in the remainder of this chapter.

POTENTIAL ENABLING TECHNOLOGIES

Advanced Air-Breathing Engines

A major constraint on improving the overall performance and lowering the cost of today's launch systems is the relatively low specific impulse of conventional rocket propulsion.[2] Air-breathing engines with their vastly superior specific impulse at lower flight speeds ($M \leq 12$) offer much improved mass ratios and more robustness in vehicle design. Unfortunately, air-breathing engines are usually more complex than rocket engines and have significantly lower thrust-to-weight ratios because of their heavier engines. In addition, the higher drag associated with atmospheric flight reduces the effective specific impulse. Nevertheless, air-breathing engines, in combination with chemical rockets, have the potential to improve payload fraction, be more robust, and would be more reusable than existing expendable launch vehicles, which would result in lower costs per pound of payload to orbit.

One possible way to reduce the weight of the air-breathing portion of combined air-breathing/rocket engines is to eliminate heavy turbo-machinery by condensing the incoming airflow and pumping the air in the liquid phase using a much smaller pump. In this scenario, the airflow would be liquefied by using the onboard cryogenic propellants in a heat-exchange process. This class of engine is called a liquid air cycle engine (LACE). In the basic cycle, air is liquefied and pumped to a rocket-thrust chamber. The liquefying agent is liquid cryogenic hydrogen, which is pumped through a heat exchanger as it, in turn, flows to the rocket thrust chambers. Although the basic LACE engine was once limited to low specific impulses (~ 1,000 sec), more sophisticated cycles were identified in the 1960s during the first U.S. Air Force Aerospace Plane Program.

Recently, research on LACE engines has been revived in Japan and Russia, where test engines have been successfully demonstrated. Significant advances have been made in heat-exchanger technologies, and problems with icing have been resolved. The Russian Space Agency's program to evaluate reusable space transportation system technologies, which began in1993, includes substantial work on LACE derivatives and air liquefaction systems.

A separate and important propulsion development related to LACE is the invention of the "deeply cooled" engine. This engine cycle is similar to LACE, but the air cooling stops short of actual liquefaction. The deep-cooling cycle has been confirmed as the basis of the British RBSUS engine, which was under development for the horizontal takeoff and landing RLV project. Analytical studies, principally in Russia, have demonstrated promising performance levels for this class of engines.

Another "cryogenic" class of engine that should be mentioned is the Japanese Air Turbo-Rocket Expander Cycle (ATREX). In this air turbo-rocket, the fan is driven by a turbine

---

[2] Current levels of specific impulse for rocket engine ranges from approximately 200 to 400 seconds, depending on the type of propellant.

powered by heated hydrogen. The hydrogen is heated by means of a heat exchanger located in the afterburner. Interestingly, a hydrogen precooler is used in the engine intake. A version of this engine has been extensively ground tested, and tests under simulated flight conditions are planned.

Unlike rocket engines, different types of conventional air-breathing engines perform best at different flight speeds. For example, turbine engines perform best from takeoff to speeds of about Mach 3.5. Subsonic combustion ramjets perform best at speeds from about Mach 2.5 to Mach 6.0; and supersonic combustion ramjets from about Mach 6.0 to Mach 12 to 15. In general, rocket propulsion is required for speeds of more than Mach 12 to 15. Consequently, propulsion from takeoff to orbit will require a multimode engine that combines air-breathing and rocket elements. The propulsion design problem can be greatly simplified by using a two-stage vehicle with separate air-breathing and rocket stages.

Unfortunately, realistic evaluations of the potential benefits of air-breathing systems for single-stage or two-stage RLVs cannot be made at this time because the basic parameters of combined-cycle engines are not known. Cost issues associated with their potential use in RLVs are also poorly understood. Therefore, a thorough technical assessment of state-of-the art systems must be made as a starting point for evaluating their promise and potential. A system design approach to this assessment should be considered, with cost as the independent variable. This assessment could then be used as a basis for an aggressive R&D program. The technical assessment should encompass the following engine concepts:

- rocket-based combined-cycle engines, including rocket-scramjet systems and rocket-ramjet systems
- interturbo-rocket engines, including the U.S. air-core enhanced turbo-ramjet engine and the innovative Japanese ATREX
- cryogenic fuel engine cycles, including LACE-derived engines and the deeply-cooled engines explored by the United Kingdom and Russia
- gas turbine engines incorporating advanced materials and better aerodynamics that could improve thrust-to-weight ratio

Finding. A system study is required to select the most cost effective combined air-breathing/rocket engine for RLVs. The study must be detailed enough to identify promising technologies and should assess the benefits of engines relative to pure rocket-based propulsion systems incorporating advanced technologies.

Pulse Detonation Wave Engine

The detonation process has been extensively studied, and over the years, sporadic attempts have been made to apply the detonation process to rocket engines. Although these efforts have met with limited success, the concept is worth another look. The benefits of a detonation wave engine include improvements in thermal and volumetric efficiency. The effective pressure ratio across the detonation wave increases chamber pressures to at least six times those of the unburned fill mixture upstream of the wave front. This means that the pulsed detonation wave engine could provide the equivalent performance of a high chamber pressure conventional rocket engine while operating at one-sixth the pressure. This represents an increase of 10 to 15 percent in potential specific impulse. Because the propellant feed pressure is so low, simpler, lower pressure discharge pumps can be used. Finally, the concept can combine both air-breathing cycle operation, using air as the oxidizer, and rocket cycle operation, using onboard propellant, which makes a detonation wave engine an attractive propulsion system for transatmospheric and reusable vehicles.

Several NASA and DOD projects are in progress under the Small Business Independent Research Program that are focused on rocket and air-breathing pulse detonation wave engine concepts to demonstrate feasibility and proof of concept. Scaling limits, process controllability, and fast acting valves for booster-sized engine concepts are critical technologies that will have to be demonstrated.

Finding. Pulse detonation wave engines could provide the equivalent performance of high chamber pressure conventional rocket engines while operating at one-sixth the pressure, representing an increase of 10 to 15 percent in potential specific impulse. Critical technologies for pulse detonation wave engines include scaling limits, process controllability, and fast acting valves for booster-sized engines.

High Thrust-to-Weight Rocket Engines

A 1995 NRC study on NASA's Reusable Launch Vehicle Technology and Test Program found that prime contractors involved in the program believed that a very high (greater than 75) sea level thrust-to-weight ratio (T/W) would be required for RLVs with rocket engine propulsion (NRC, 1995). Currently, the T/W goal for the Lockheed Martin Venture Star RLV is 83. This T/W target represents increases of approximately 30 percent over both the space shuttle main engine (and the Russian Energia RD-0120, both of which are operational, high performance engines. Achieving this very difficult target will require the technical evolution of current materials and component designs that will not be proven until early in the next century.

Technology advancements beyond those that have already been identified will be necessary for NASA to realize its low cost per pound to LEO goals. Sea level T/W goals should be higher (≥ 100) for reusable lightweight vehicles with appropriate lifespans and design margins. Advanced materials and fabrication methods will have to be developed to reduce weight, raise allowable operating temperatures and pressures, dampen vibrations, increase strength, and enable revolutionary system designs. Every engine component, including ducts, valves, manifolds, and casings should be considered an opportunity for innovative improvements in technology.

Finding. The thrust-to-weight ratio necessary to enable rocket propulsion-based RLVs to meet the NASA launch cost goals will require significant reductions in the weight of engine components. Advanced materials and fabrication methods will have to be developed to reduce component weight without compromising performance.

Variable Expansion-Ratio Nozzles

The optimum thrust coefficient for a rocket nozzle is achieved at an expansion ratio where the exit pressure of the exhausting gases matches the ambient pressure. Launch vehicle booster rockets used today all have fixed-area ratio nozzles. A booster rocket flying through the atmosphere can only match the pressures at one point in altitude. At all other altitudes, the nozzle is either under-expanded, or over-expanded, which causes a slight reduction in the exhaust velocity and, thus, a loss of energy. Nozzles for booster rockets are designed for an area ratio that minimizes the loss of specific impulse over the entire flight path.

Increasing the specific impulse is important for all classes of launch vehicles. However, because of the premium on performance, advantages associated with variable expansion-ratio nozzles will especially benefit RLVs, especially single-stage-to-orbit RLVs.

Although the exact thrust specific impulse benefit will depend on the engine design and flight profile of a given launch vehicle, variable expansion-ratio nozzles enable efficient altitude compensation that increases the average nozzle thrust coefficient over that of a conventional fixed area-ratio nozzle. The concept has existed for more than 30 years, and a variety of shapes and configurations have been studied in wind tunnels and experimental rocket engine firings have been tested at small and moderate scales. Plug nozzles and expansion-deflection nozzles have been studied the longest. Aspirating slot nozzles have recently been investigated as well. Lockheed Martin is incorporating a linear aerospike (plug-like) nozzle version into the X-33, but the annular aerospike should be investigated for other RLV concepts.

A variety of other concepts have also been investigated, such as dual-throat, dual-bell, extendible cones. Although they do not provide continuous altitude compensation, they do incorporate step changes in area ratio. These concepts are not optimum, but they do provide better trajectory averaged performance than fixed area-ratio nozzles. The dual-bell cone has an added advantage in that it induces separation in the near sea-level mode, which increases sea-level thrust, an attractive feature for some RLV designs.

All of these variable expansion-ratio nozzle concepts should increase overall engine T/W and should affect vehicle design in a way that reduces overall RLV structural weight requirements.

Finding. Variable expansion-ratio nozzle configurations provide altitude compensation to improve trajectory averaged performance. To be most beneficial to RLVs, these nozzle configurations should be lightweight, should contribute to increases in overall engine T/W, and should reduce overall structural weight requirements.

Advanced Propellants and Storage Methods

The rocket propellants in use today were developed more than 30 years ago, and the potential energy of these propellants is close to the maximum. Nevertheless, the launch community, both government and commercial, will continue to rely on chemical rocket propulsion for the foreseeable future. Therefore, technology breakthroughs in propellant performance, density, and affordability will be crucial to satisfying NASA's space transportation goals. Current research on rocket propellant capability is being led by the Air Force, which has maintained a small research program in this technology area for the past 10 years. However, this program is not sufficient to bring new concepts and technologies to fruition and would benefit from the aggressive participation of NASA. The technologies that should be investigated in a more robust program are discussed below.

Recombination of Highly Energetic Atomic Ingredients

Several schemes for achieving significant increases in specific impulse performance and density are possible based on the energy and low molecular weight of hydrogen. Proposed concepts for study include cryogenic solid hydrogen, metallic hydrogen, the carbon and carbon-boron absorptivity of hydrogen, and cryogenic solid oxygen. These propellants could provide specific impulse increases as high as 200 seconds over today's state of the art, and could be the basis for achieving launch costs of less than $100 per pound of payload to LEO.[3] Improvements in performance with solid hydrogen are achieved by exploiting the recombination energy of energetic atomic ingredients, such as boron, carbon, hydrogen, and lithium. Approaches being pursued involve packaging these energetic and reactive ingredients in cryogenic solid matrices in order to separate them physically from one another by the hydrogen host molecules. A similar approach uses a mixture of ozone in solid oxygen with a potential increase in specific impulse of up to 50 seconds.

Steady progress has been made in research on cryogenic solid propellants. Laboratory experiments have demonstrated the feasibility of ingredient storage, albeit at low concentrations, and small thruster experiments have demonstrated the stable combustion of pure cryo-solid propellants in a hybrid configuration. Much more research will be necessary before this can be called a breakthrough technology and before its readiness for transition into real launch systems can be demonstrated. Research areas are listed below:

[3]Current levels of specific impulse for rocket engines range from approximately 200 to 400 seconds, depending on the type of propellant.

- computational studies of the dynamics, thermodynamics, and spectroscopy of energetic additives to cryogenic solids
- spectroscopic characterization of highly energetic species trapped in energetic matrices at concentrations of at least 1 percent
- production methods for energetic species
- scale-up production of cryogenic solid propellants with energetic species concentrations of at least 1 percent
- methods of transporting and combusting doped cryogenic solids

Hydrogen Storage at High Effective Densities

In many ways, hydrogen is the ideal chemical rocket propellant. Its one great disadvantage is its extremely low storage density as a cryogenic liquid. If a way can be found to store hydrogen at ambient temperature, in an absorbed or adsorbed state and at an effective density much higher than liquid hydrogen (.07 gm/cc), this could be a real breakthrough for the transportation industry as a whole (automotive, aircraft, and space).

Recently, a number of researchers have reported the development of carbon nanotubes that are capable of absorbing/adsorbing large quantities of gas, such as hydrogen (Dillon et al., 1997). The effective density of the adsorbed material may be substantially increased as a consequence of the attractive potential of the pore walls, where pores are of molecular dimensions. These results suggest that nanofibrous carbon material may have the capability to store hydrogen at very high effective densities, which would mean that much smaller and lighter tanks and associated structures could be used in a hydrogen-fueled launch vehicle. Although the properties of these carbon materials are still being explored in the laboratory, and there will probably be some challenges with respect to the large-scale production of carbon nanotubes, this technology could contribute to the development of a truly low-cost single-stage-to-orbit vehicle.

Metallic Hydrogen

Metallic hydrogen is the optimum form of solid hydrogen and consists of all hydrogen atoms in a disassociated metallic state. There have only been glimmers of feasibility in the synthesis of metallic hydrogen, but because of its high payoff (up to 1,200 sec specific impulse) some investment by NASA in research on metallic hydrogen would be warranted.

Finding. Notable improvements in chemical propellants, which could be important to the achievement of NASA's space transportation goals, are possible. Potential advances include the recombination of highly energetic atomic ingredients, hydrogen storage at high effective densities, and the development of metallic hydrogen. However, the potential of these advances may not be realized unless NASA increases its research support.

Integrated Aerothermal Structures

In order to reduce launch costs, tremendous advances will have to be made in most, if not all, parts of the space transportation system. The committee believes that an area of equal importance to advanced propulsion technologies and advanced propellant technologies is the airframe, or integrated aerothermal structure, of the reusable launch system. This highly integrated structure must efficiently incorporate the entry thermal protection system, as well as the propulsion system and propellants. Integration will be particularly complex if some form of air-breathing propulsion system must also be integrated into the airframe. Systems studies will be necessary to select the most cost-effective integration strategies for launch vehicles.

Improvements in the following enabling technologies will be necessary for the production of durable, long-life, integrated thermostructures:

- integrated cryotank/insulation/thermal protection system designs
- attachments, joints, and seals
- long-life, durable thermal protection systems and cryotank material development
- vehicle-integrated conformal/integral designs
- purge, vent, and cooling provisions
- composite cold structures
- ceramic hot structures

Each of these technologies will have to be life-cycle tested in representative environments for thousands of cycles to assess their robustness.

Finding. For RLVs designed to achieve NASA's launch cost goals, lightweight, integrated aerothermal structures will be critical. System studies should be performed to select the most cost-effective integrated thermostructure. Technology development will also be required for a number of critical subsystems.

Novel Launch System Concepts

Achieving the NASA cost goals may require revolutionary concepts and somewhat unconventional approaches to launch systems. Many concepts in this category, such as electric and solar propulsion, solar sails, and most forms of nuclear propulsion, are most appropriate to orbital transfer vehicles or station keeping. Nuclear propulsion could be a high thrust device suitable for boosters, but the public is not likely to accept this technology for use in this application. Antimatter is a speculative, yet feasible, approach that has great potential if it can be stored in quantity and the energy release mechanism can be harnessed. Laser propulsion is another promising idea that is already under investigation.

Ground-based techniques that assist the launch vehicle, including rocket sleds, "mag lev" rails, and pulse detonation tubes, are also being investigated. However, the committee believes that these concepts, although they may be technically feasible, only address "niche markets" for access to space. The very high acceleration loads on payloads launched by these techniques would probably limit their utility to a small, but perhaps very important class, of payload, including propellants and rugged structures, which will be important when an in-orbit infrastructure for assembly and refueling is developed. However, novel launch vehicle configurations and automated launch operations based on systems approaches aimed at reducing costs and increasing reusability appear to have wider applicability and may approach NASA's first launch cost goal.

Novel Launch Vehicle Configurations

Compared to the accepted design configurations for expendable launch vehicles, all RLVs in use or being considered are novel or unconventional. This began with the Space Shuttle, and continued with the Boeing (formerly McDonnell Douglas) DC-X/DC-XA, with its vertical takeoff, vertical landing demonstrations. The committee was briefed on many of the RLV concepts currently under development, including the NASA-funded X-33 and X-34 projects, the Air Force-funded Space Operations Vehicle and Space Maneuvering Vehicle demonstrators, and two of the many privately funded approaches to reusability[4].

The committee did not analyze any of these RLV concepts in any detail. However, the committee believes that NASA's first access to space goal of $1,000/pound to LEO could potentially be achieved by 2010 using systems engineering approaches that combine demonstrated technologies and infrastructure into a launch capability optimized for minimum total cost and reusability.

Automated Launch Operations

Reducing the cost of labor-intensive launch operations through automation is another important component of reducing launch costs that should be pursued in parallel with novel launch vehicle concepts. Increased automation should be based on optimization of human/computer interactions during the design stage of launch vehicles and their related launch infrastructures, and from enhanced human/computer integration in launch processing and operational command and control.

Finding. Leveraging novel reusable launch vehicle concepts and automated launch operations based on demonstrated technologies and systems approaches aimed at reducing costs and increasing reusability may approach NASA's 10 year launch cost goal.

---

[4] Space Access LLC and Kelley Aerospace Corporation presented their concepts to the committee. Other reusable launch vehicle concepts are currently being designed or developed by commercial launch vehicle firms such as Pioneer Rocketplane, Inc., HMX, Incorporated, and Kistler Aerospace Corporation.

REFERENCES

Dawson, T. 1994. Perspectives on U.S. Space Launch Systems—A Staff Background Paper. Subcommittee on Space, Committee on Science, Space and Technology, U.S. House of Representatives, Washington, D.C.

Devere, T. 1998. E-mail to the Committee to Identify Potential Breakthrough Technologies and Assess Long-term R&D Goals in Aeronautics and Space Transportation Technology from Taft Devere, U.S. Space Command, June 12, 1998.

Dillon, A.C., K.M. Jones, T.A. Bekkedahl, C.H. Klang, D.S. Bethune, and M.J. Heben. 1997. Storage of hydrogen in single-walled carbon nanotubes. Nature 386 (Mar 27): 377–379.

NRC (National Research Council). 1995. Reusable Launch Vehicle Technology Development and Test Program. Aeronautics and Space Engineering Board, Committee on Reusable Launch Vehicle Technology and Test Program. Washington, D.C.: National Academy Press.

6

Breakthrough Technologies to Meet NASA's Goals

IDENTIFYING BREAKTHROUGH TECHNOLOGY CATEGORIES

At the end of the workshop on breakthrough technologies described in Chapter 1 and Appendix E, the committee identified the technologies that were described in the preceding three chapters. The committee then attempted to identify broad areas of technology development that could lead to breakthrough capabilities in both air and space transportation and that could potentially meet many of NASA's goals for aeronautics and space transportation technology. Because NASA's budget for aerospace R&D is limited, the committee believes that identifying crosscutting technologies is critical. Although all of the technologies discussed in the previous chapters deserve funding consideration by NASA, the five breakthrough technology categories listed in this chapter represent the committee's priority areas of focus (see Table 6-1). The committee believes that these five categories are also suited to NASA's role of "pushing the technological envelope" by supporting the development of high risk, but potentially high payoff technologies that are not likely to be supported by U.S. industry based on conventional commercial investment criteria.

Although the five categories of research and technology development are discussed separately below, they are interrelated in many ways, just as the 10 national goals defined by NASA for air and space transportation are interrelated. To ensure that meeting any one goal does not adversely affect meeting another, technology must be developed with a broad and comprehensive understanding of the entire air and space transportation system. This will require the cooperation of all organizations involved in the nation's aerospace R&D enterprise, including NASA, the FAA, DOD, universities, and industry. However, NASA is well structured and broad-based enough to play a unique role in the analysis and development of technology for the "aerospace" transportation system. Because NASA's R&D programs intersect engineering and risk exploration, the agency is in a unique position to bring insight to the potential synergism and trade-offs of new component insertion, technology integration, and operational interaction. NASA can act as the steward of crosscutting, "system of systems" technology analysis, which could be called enhanced systems engineering.

TABLE ES-1 NASA's Goals for Aeronautics and Space Transportation Technology and the Recommended Breakthrough Technology Categories

Breakthrough Technology Category	Reduced Emissions	Reduced Perceived Noise Levels	Reduced Aircraft Accident Rate
Cyber Technology			
Modeling and simulation	M	M	H
Advanced, robust, real-time sensors and actuators	M	**H**	M
Automated manufacturing	L	L	L
Improved methods for developing flight-critical software	M	M	**H**
Human-computer integration	M	M	**H**
Structures and Materials			
Lightweight structures	L	L	L
High-temperature materials	M	L	L
Propulsion Technology			
Advanced air vehicle propulsion concepts	**H**	**H**	L
Advanced propellants for launch vehicles	—	—	—
Aerospace Vehicle Configurations			
Advanced configurations	M	M	L
Precision Air Traffic Operations in Terminal Areas			
Reduced runway occupancy time	L	—	M
Mitigation of wake vortices	L	—	M
V/STOL air vehicles	L	M	—

L = Low impact on achieving the goal; M = Moderate impact; H = High impact.

Triple Aviation System Throughput	Reduced Air Travel Costs	Increased Design Confidence and Reduced Cycle Time	Invigorated General Aviation Industry	Reduced Travel Time	Reduced Payload Cost to Low Earth Orbit
H	M	**H**	M	M	M
M	M	M	L	L	M
L	M	M	**H**	M	M
M	M	**H**	M	L	—
M	M	**H**	**H**	M	M
L	M	M	**H**	**H**	M
L	M	M	M	**H**	M
L	**H**	L	M	**H**	—
—	—	—	—	—	**H**
M	M	L	M	**H**	M
H	M	—	M	L	—
H	M	—	M	L	—
H	M	—	M	L	—

CYBER TECHNOLOGY

The prefix "cyber," when used in words such as cybernetics, cybernation, and recent expressions such as cyberspace, connotes a merging of human control over processes and physical activities with computer-based control. For this reason, the committee has chosen the term cyber technology to encompass a host of technologies and concepts related to the growing importance of computer-based information and control systems to air and space transportation and the design and manufacture of aerospace systems.

Cyber technology will be pivotal to the achievement of all of NASA's goals for aeronautics and space transportation technology. However, it would be unrealistic for NASA to play a critical role in R&D related to all of the technologies that fall into this category. For example, continuing improvements in computer microprocessor speed and capability do not require NASA's attention. However, the committee believes that five of the cyber technology areas discussed in Chapters 3, 4, and 5 are crucial to meeting NASA's goals. These five areas will not receive adequate levels of R&D focused on aerospace applications without support from NASA. The five cyber technology areas are: modeling and simulation for both vehicle design and the characterization of the air transportation system; advanced, robust, real-time sensors and actuators for air vehicle structures, materials, and propulsion systems; automated aerospace manufacturing and space launch operations; improved methods for developing flight-critical software; and optimized human-computer interactions for aircraft flight decks and for the process of aerospace vehicle design.

Modeling and Simulation

Modeling and simulation has developed at a very rapid pace during the past several decades, and NASA's past activities in this area have been noteworthy. For example, the initiation and support of computer programs such as NASTRAN (NASA structural analysis), have provided invaluable design capabilities to the aerospace industry. Today, literally hundreds of models are used to simulate physical systems. However, multiscale models and simulations that can predict the effects of changes in any component or at any scale of a system and propagate them throughout the whole system are still in the development stage. For example, changes in aerospace material properties at the molecular level, such as creep and fracture toughness, can have significant effects at the component level, such as a wing or an airframe, that will alter performance at the macrolevel, in this case, the air vehicle. The capability to link molecular phenomena to macroscale phenomena in an acceptably predictive manner has not been developed. Therefore, a significant area for research in this important area is the integration of models to provide an "unbroken chain" of simulation capability from the atomic scale to the structural scale to the system interaction scale. Models at any given scale must be connected to models at the next larger and next smaller scales.

Making the most effective use of simulations in the design process will require a capability to seamlessly integrate models of one level of fidelity with models of a different level. For example, results from a detailed three-dimensional model should be able to be fed back into a less detailed two-dimensional model. The architecture for doing this has yet to be developed.

Models of physical properties at a larger scale than the air vehicle will also be necessary to simulate the properties of the entire air transportation system. Here the scale can be thousands of miles and cover the entire airspace of a nation or regional area. An additional challenge posed by the simulation of an entire air transportation system is the modeling of human and socioeconomic behaviors. For simulations of large-scale physical systems or systems comprised of both human and physical behavior, explicit treatment of uncertainties in each fundamental model that comprises the total integrated simulation will be essential.

The committee believes NASA's role should be to integrate and verify physically and cognitively accurate models and simulations of aerospace systems. This will require complete knowledge of modeling and simulation R&D being funded by DOD, the NSF, and the aerospace industry so gaps in specific modeling capabilities at various scales can be identified. It will also require that NASA support research on structuring fundamental models to compensate for uncertainties so the realism of the whole simulation will be greater than the sum of its parts.

Advanced, Robust, Real-time Sensors and Actuators

Advanced sensor and actuator technologies for aerospace applications should eventually provide for the active, real-time control of vehicle performance and safety. Embedding sensors and actuators within structures and materials will create intelligent or "smart structures" with properties that enhance performance through controlled structural deformation and health monitoring that detects damage and determines remaining useful life.

Similarly, closed-loop feedback in propulsion systems could potentially reduce the emissions of environmentally sensitive products of combustion and could control aerodynamic, aerothermodynamic, and aeromechanical instabilities through embedded sensors and controls. Conventional sensor technology will have to be improved in two ways. First, new sensor materials and systems will have to operate at higher turbine inlet temperatures. Second, the scale of conventional sensors will have to be reduced to minimize interference. Nonsilicon-based MEMS have the potential to meet these requirements.

Onboard weather detection sensors and systems can affect the safe operation of existing and future air vehicles. The detection of clear-air turbulence and local instabilities, such as trailing edge vortices, could allow pilots to avoid them. In addition, sensors for the early detection of ice and other deposits on wings and lifting surfaces could improve safety during severe weather.

Priority areas for R&D on advanced sensor and actuator technologies include: the development of robust actuators and sensors (thermal and chemical) for use in hostile environments; further development of MEMS for use in intelligent systems; and the integration of these systems into air vehicle components.

NASA's most practical role in the development of advanced sensor and actuator technologies may be as a systems integrator, in partnership with the private sector, and as a source of basic scientific knowledge related to the physical properties that sensors are designed to observe. NASA research programs could also fill specific technology gaps, such as usable materials for robust sensors. DOD and NSF research in this area should be carefully coordinated with NASA programs.

Automated Manufacturing

Labor and associated overhead are two of the major cost elements in the manufacture of an aircraft and its component systems. Therefore, reducing these costs through increased automation would reduce the overall cost of acquiring new aircraft. Lower aircraft purchase costs for airlines could contribute to the NASA goal of reducing the cost of air travel, and reducing the cost of new general aviation aircraft could help meet the NASA goal of reinvigorating this sector of the aerospace industry. Manufacturing is an essential element of aerospace product development and should have an influence on the design of an air vehicle beginning with conceptual design. NASA can support the integration of manufacturing into the whole air vehicle production and development process by investigating automated fabrication processes, such as manufacturing by light, that could directly link design databases to finished assemblies.

Improved Methods for Developing Flight-Critical Software

Virtually all modern systems of any complexity, including aviation systems, are governed by software. As the complexity and size of these software systems grow, their behavior is likely to become less predictable. However, many aviation systems that rely on software are safety critical, meaning that malfunctions would put lives at risk. Therefore, software development methods should focus on ensuring that critical software operates as expected under *all* conditions. Some approaches may be emerging in current software R&D, but they have only been successfully used in relatively simple digital systems. Verifying complex avionics software, including interfaces to analog components and to human operators, will require continued research.

Perhaps the most important software in a commercial aircraft helps the pilot monitor or even fly and land the plane. Chapter 4 in this report points out the growing importance of autonomous flight, the use of precision sensors, and dynamic controls, all of which will be augmented by software. Thus, the behavior of flight-critical software will have to be predictable. Only completely predictable and reliable software will be accepted as a means of improving crew performance.

NASA and others have been investigating formal approaches to software development that are still too complex to understand and apply. New development approaches, such as formal methods, may be able to demonstrate that software will do what it is expected to do and can find and exclude unintended actions. The latter task is much more difficult and will require breakthroughs in software design techniques. Such methods will have to reveal functional interactions, intended and unintended, in both the system models and the software that represents them. Because of their underlying complexity, the competitive atmosphere, and possible litigation, industry is not likely to develop these methods itself. However, if these methods could be made usable to software designers, industry would certainly use them.

Human-Computer Integration

In the past three decades, the power of computation has increased exponentially. Computers today have realized much of their expected potential for controlling and/or simulating complex phenomena in real time through advances like parallel processing. The real potential for terahertz computation rates will further advance the power of computers. Yet the full potential of computing and information technology for aerospace applications, such as the safe and efficient operation of aircraft and the design of aerospace vehicles, will not be realized until interactions between humans and computers have been improved.

Although humans are the most advanced sensors and actuators in existence, occasional lapses in action or concentration, and the inability to process information at desired rates, can, and often does, lead to system failures. However, optimized human and machine task allocation and integration could change the situation as dramatically as the advent of the wheel, the mechanical lever, and the airfoil.

Improvements in human-computer integration as it relates to the design of aerospace systems, such as aircraft and launch vehicles and their components, will be based on an understanding of the creative process, which is essential to design and cannot be duplicated by machines. If artificial agents, expert systems, and sensory interfaces involving virtual reality can be designed to link human creativity to realistic, physics-based computer models and simulations, complete prototypes could be designed and flown in a fully virtual environment. Thus, near optimum configurations could be realized without ever conducting physical tests.

Current assumptions about the allocation of tasks to humans and computers will require significant reappraisal to improve human-computer integration for aircraft operations. This reappraisal will require advanced methodologies to evaluate complex human-computer interactions based on advanced simulation and the collection and analysis of multi-attribute field data. In the meantime, until unpiloted commercial transport aircraft become socially acceptable, information must be organized, refined, and presented to pilots in a manner that effectively maintains their situation awareness. Given the extraordinary amount of data that should be available from inward-looking and outward-looking onboard sensors and external sources of information, a comprehensive systems approach to situation awareness will be critical.

More automated space launches will also require improved human-computer interactions. Automation could reduce or eliminate many costs related to launch processing and operations that are currently labor intensive and should contribute to the achievement of NASA's goals to reduce launch costs.

Broad, long-term R&D to improve human-computer integration in aerospace systems will probably require substantial support from NASA. Everything from the development of advanced methods for software development to basic research on human cognition would benefit from the oversight and integration that a single sponsor such as NASA could provide. However, the results of research supported by the NIH, NSF, and DOD should also be integrated with the results of NASA's own programs.

Recommendation. NASA should focus its aeronautics and space transportation research and technology development to meet the 10 goals on the following areas of cyber technology: modeling and simulation applied to both vehicle design and the characterization of the air transportation system; advanced, robust, real-time sensors and actuators for air vehicle structures, materials, and propulsion systems; increased automation of aerospace manufacturing and space launch operations; improved methods for developing flight-critical software; and improvements in human-computer integration for aircraft operations and aerospace vehicle design.

STRUCTURES AND MATERIALS

Over the last three decades, revolutionary advances in structures and materials technology have resulted in significant improvements in aerospace vehicle structural efficiencies and performance characteristics. Progress in this field is expected to continue unabated. Combined with improved computational methods, advances in materials science (including increased understanding of material behavior, characterization, and structural analysis), advances in manufacturing methods (including processing science), concurrent, computer-aided design, and intelligent health monitoring systems, structures and materials technologies will substantially improve aerospace vehicles. Advances in lightweight structures for RLVs and improvements in the general area of high-temperature materials will be critical to meeting a number of NASA's goals.

Lightweight Structures for Reusable Launch Vehicles

Reducing the weight of the aeroshell or integrated aerothermal structure of a RLV will be necessary for meeting NASA's goals for low cost launch. Lightweight materials and designs will have to be developed for a number of sub-components including: the insulation/thermal protection system; attachments; joints and seals; the cryogenic tank; the composite cold structure; and high-temperature ceramic materials systems.

Weight reductions in the propulsion system will also be necessary, with an emphasis on the development of high temperature metallic alloys, ceramics, intermetallics, and polymer composites. These materials will allow both higher operating temperatures and reductions in weight, while maintaining durability and manufacturability. Many systems components, including ducts, valves, manifolds, and casings, could be improved with new materials designed for lower weight.

High-Temperature Materials

High-performance aerospace vehicles, such as RLVs and supersonic aircraft, require materials systems that can perform satisfactorily in thermal environments ranging from moderate to extreme. For example, the contemporary materials under consideration for a Mach 2.4 high-speed civil transport, including conventional aluminum alloys, titanium alloys, polymer composites, fuel tank sealants, adhesives, and finishes, must perform adequately at temperatures from – 65°F to 320°F (350° for leading-edge structures) for a minimum of 60,000 hours at maximum temperature. So far, none of these materials has demonstrated the necessary weight and long-term temperature durability characteristics (NRC, 1997). Therefore, NASA should increase its support for basic materials R&D. Material manufacturability, maintainability and cost must be considered in addition to temperature and weight characteristics.

The development of suitable engine materials for the high-speed civil transport should focus on advanced metals, ceramics, intermetallics, and metal-ceramic composites. Other areas for R&D include advanced coatings technology for metals and ceramics, ceramic fibers, and advanced manufacturing technology for net shaped forming.

New materials will also be required for the thermal protection systems of RLVs, which must undergo repeated reentry into Earth's atmosphere. Conventional thermal protection systems have not demonstrated the durability or cost properties necessary to meet the NASA goals.

Recommendation. Because immediate breakthroughs in the development of lightweight structures and high-temperature materials suitable for high-speed civil transports and reusable launch vehicles are not readily apparent, NASA should invest in fundamental research on structures and materials research, keeping in mind important end use requirements, such as affordability, manufacturability, and maintenance.

PROPULSION TECHNOLOGY

Advanced Air Vehicle Propulsion Concepts

NASA's goals related to emissions, noise, cost, general aviation, and high-speed air travel will all be impacted by advances in propulsion technology. Major opportunities include: step changes in the gas turbine engine through the development of novel components using active control, such as aspirated compressors, with fewer, more slowly turning counter-rotating blade rows; and alternative propulsion systems, such as detonation wave engines and fuel cells.

Novel Components and Active Control for Gas Turbine Engines

Novel methods to control flows in aeropropulsion and fluid machinery components include suction within the inlet and suction and blowing in nozzle/ejector components which would help control tonal noise. Controlled suction in "aspirated" compressor blades and end-wall surfaces would increase operating margins, improve stall/surge control, and increase T/W (thrust-to-weight) ratios. Active control could also be used to reduce engine emissions created during the combustion process. Real-time, detailed diagnostic sensors, such as optical or MEMS-based sensors, combined with closed-loop controllers and actuators operable at the microscale are areas requiring R&D.

Alternative Propulsion Systems

Eliminating complicated rotating machinery for high-speed propulsion systems appears to be a worthwhile goal. The detonation-wave engine is one approach that has the potential to increase specific impulse levels based on the basic thermal efficiency benefits of the Humphrey cycle over the turbine engine Brayton cycle. Technological challenges that require additional research include high noise levels, control issues, and the stability of detonation.

Fuel cells appear to be a promising source of propulsive power for subsonic air vehicles, but they will require a great deal more development before they will be truly practical. The advantages of fuel cells include low fuel consumption compared to conventional propulsion systems and extremely low (zero, in some cases) production of pollutants (NO_x, CO and CO_2). In addition, the chemical power conversion efficiency of fuel cells is about twice as high as the thermodynamic power conversion of standard propulsion systems. Determining if fuel cell propulsion technologies can be made feasible from a total vehicle system perspective will require aircraft design studies involving fuel cells. Investments in other areas where NASA has expertise, such as fuels and material development for fuel cells, will also contribute to their potential as useful power sources for air vehicles.

Recommendation. NASA's investments in propulsion technologies to meet the goals for air transportation should focus on new technologies that offer step changes in the performance of gas turbine engines. NASA should also support research on alternative propulsion and power technologies, which will require aircraft design studies as early in the development process as possible to assess potential benefits.

Advanced Propellants for Launch Vehicles

Despite potential advances in air-breathing launch vehicles and ground-based launch assist techniques, such as magnetically levitated rail guns, the committee believes that rocket-based or combined rocket-air-breathing propulsion systems will continue to be technologies of choice for the commercial launch industry. Therefore, technology breakthroughs in propellant performance, density, and affordability will be crucial to satisfying NASA's space transportation goals. Technologies that should be investigated include cryogenic solid hydrogen, metallic hydrogen, the carbon and carbon-boron absorptivity of hydrogen, and cryogenic solid oxygen. These propellants could provide increases in specific impulse as much as 200 seconds over the current state of the art, and could provide a basis for reducing launch costs to less than $100 per pound of payload to LEO.

A number of research projects on the use of hydrogen for various power and propulsion systems, including fuel cells, are under way, but none of these efforts are focused on rocket propellants. Current government-sponsored research in advancing rocket propellant capability is being led by the Air Force, but it is not sufficient to bring new concepts and technologies to meet NASA's goals to fruition. Therefore, the committee believes that aggressive participation by NASA, with close cooperation between the Air Force Rocket Laboratory and NASA's Marshall Space Flight Center, will be necessary.

Recommendation. To reduce launch costs, NASA should become a full partner with the U.S. Air Force in the development of advanced rocket propellants. This joint program should focus on cryogenic solid hydrogen, metallic hydrogen, the carbon and carbon-boron absorptivity of hydrogen, and cryogenic solid oxygen.

AEROSPACE VEHICLE CONFIGURATIONS

The overarching necessity for the total integration of component technologies in the development of air vehicles will require that both conventional and unconventional configurations continue to be explored to accomplish NASA's goals. However, the committee believes that unconventional advanced configurations have a better potential for achieving these goals.

Advanced Configurations

The BWB (blended-wing body) is an example of a promising new design concept that could further NASA's goals of reducing costs, emissions, and noise. However, other designs may also have the potential to achieve a number of NASA's goals and should be assessed. In general, overall aerodynamic performance can be enhanced by highly integrated configurations. Although industry may make limited investments in preliminary design studies focused on unconventional configurations, full scale, or even subscale, testing will probably not proceed without substantial participation by NASA.

Recommendation. NASA should continue to support preliminary feasibility studies for advanced air and launch vehicle configurations designed with new levels of propulsion/airframe/aerodynamic integration. Configurations that have the potential to meet several goals, like the BWB, should undergo extensive virtual testing and/or full-scale experimental vehicle development.

PRECISION AIR TRAFFIC OPERATIONS IN TERMINAL AREAS

The nation's air transportation system and the air transportation systems of other highly developed areas, such as Europe, are fundamentally constrained in terminal environments. No matter how precise navigation and surveillance become for air traffic en route from one terminal area to another, the total throughput cannot be increased unless more cargo, passengers, and private pilots can take off and land in a given area in a given period of time. The committee is not convinced that public use airports will be built or expanded to accommodate projected higher levels of air traffic. Therefore, the solution to increases in terminal area capacity must come from breakthrough technologies and associated procedures.

A wide range of candidate improvements in aircraft, airport, and ATM technology should be evaluated to reduce terminal area constraints. Even personal air vehicles (discussed in chapter 4), are a possible solution that should be considered, although their widespread use is probably decades away. However, to meet the 10-year goal of tripling aviation system throughput, the committee believes that NASA should focus on the development of technologies and procedures for reducing runway occupancy time, mitigating wake vortices, and increasing the use of V/STOL air vehicles at existing airports. Existing government-funded initiatives focused on increasing throughput at airports, such as NASA's capacity and terminal area productivity programs, should support R&D in these three areas.

Reduced Runway Occupancy Time

Runway occupancy time during landing operations is currently governed by the amount of time it takes an aircraft to proceed from the runway threshold crossing to a runway exit after touchdown. This, in turn, is dependent on the amount of time needed to slow the aircraft sufficiently so that it can safely turn off the runway. Quicker deceleration through the combination of new runway surface materials and aircraft systems, such as actively controlled brakes and brake guidance systems, could increase deceleration profiles and exit speeds.

Another way to approach the problem is to allow more than one aircraft to occupy the runway at a given time. Two or more aircraft could land at different touchdown points on the same runway, either in parallel on wide runways or in-trail on long runways. Advanced flight control systems, aircraft-to-aircraft surveillance, and pilot-controller decision aids could ensure that safe spacing between the aircraft is maintained. To be most beneficial, this capability is needed for both visual flight and instrument flight operations. The necessary technologies include very precise control of aircraft position and velocity in all four dimensions and precise position tracking with very rapid updates of aircraft position and intent. Onboard collision avoidance systems would also have to be more highly automated than the systems currently in use.

Mitigating Wake Vortices

Wake turbulence created by vortices emanating from aircraft wings limits en route in-trail spacing, takeoff and landing spacing, and the spacing of runways at airports. Therefore, the mitigation of wake vortices would have a major impact on reducing terminal area delays. Possible technological approaches to mitigation include the development of sensor systems that can detect and measure wake vortices and the development of methods to reduce or control vortices. Procedural approaches to "managing" wake vortex encounters safely include displaced runway thresholds, variable glide path approaches, precision approach paths for all weather operations, and dynamic encounter aids associated with advanced sensors. NASA should vigorously support research on all of these technologies and procedures.

Vertical/Short Takeoff and Landing Aircraft to Enhance Capacity

Although V/STOL aircraft usage in the commercial transport market has always been limited because of unfavorable economic projections, these vehicles could serve the short distance air travel markets cost effectively if they could operate from existing airports. If they could also operate without decreasing the capacity available for conventional runway operations, overall throughput would be increased. This potential capability, known as simultaneous noninterfering operations, is currently being investigated by Boeing

Helicopter and NASA Ames Research Center. Simultaneous noninterfering operations would require the same technologies that would enable multi-aircraft runway occupancy.

Considerable vehicle technology development for V/STOL aircraft, such as tiltrotors, will be necessary to make them economical, reliable and safe. Therefore, R&D on propulsion systems, structures and materials, and vehicle configurations should be assessed for their potential applicability to V/STOL aircraft.

Recommendation. To further the goal of tripling the aviation system throughput in 10 years, NASA should support R&D focused on mitigating terminal area constraints. The most promising areas of focus include the reduction of runway occupancy time, the mitigation of aircraft wake vortices, and the operation of V/STOL air vehicles at existing airports. Existing government-funded initiatives which are seeking to improve throughput at airports, such as the NASA Terminal Area Productivity program, should support R&D in these three areas.

REFERENCE

NRC. 1997. U.S. Supersonic Commercial Aircraft: Assessing NASA's High-Speed Research Program. Aeronautics and Space Engineering Board, Committee on High Speed Research. Washington, D.C.: National Academy Press.

Acronyms and Abbreviations

ADS	automatic dependent surveillance
ATC	air traffic control
ATIS	air terminal information system
ATM	air traffic management
ATREX	Air Turbo Rocket Expander Cycle
BWB	blended-wing body
CFD	computational fluid dynamics
CNS	communications/navigation/surveillance
CO	carbon monoxide
CO_2	carbon dioxide
DOD	U.S. Department of Defense
FAA	Federal Aviation Administration
GPS	Global Positioning System
LACE	liquid air cycle engine
LEO	low-earth orbit
MEMS	microelectromechanical systems
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NO_X	nitrous oxide

NRC	National Research Council
NSF	National Science Foundation
NSTC	National Science and Technology Council
ODW	oblique detonation wave
OSTP	Office of Science and Technology Policy
PDW	pulse detonation wave
R&D	research and development
RLV	reusable launch vehicle
SO_2	sodium dioxide
TRL	technology readiness level
T/W	thrust-to-weight ratio
UAV	uninhabited air vehicle
V/STOL	vertical/short takeoff and landing
V&V	validation and verification

APPENDICES

APPENDIX A

Statement of Task

The objectives of the study are to:

(1) Identify a small number of revolutionary or breakthrough technologies that can be critical to the 20–25 year future of aeronautics, based primarily on the areas of need and opportunity that were identified in the Phase I study. The identified technologies can be expected to represent high risk, but potentially very high payoff investments. Technologies with potential military, as well as civil, applications may be considered if they are appropriate potential components of NASA's advanced basic R&D program.

(2) Assess how these concepts and technologies can address the multiple needs that were identified in Phase 1.

(3) Examine the long-term aeronautics R&D goals that NASA has developed and comment on whether they are consistent with the findings and recommendations of this study and whether they are likely to be achievable, either through evolutionary steps in technology or through the identification and application of breakthrough ideas, concepts, and technologies.

APPENDIX B

Biographical Sketches of Committee Members

R. BYRON PIPES, *chair*, NAE, was president of Rensselaer Polytechnic Institute from 1993 to 1998. He was provost and vice president for academic affairs at the University of Delaware from 1991 to 1993 and served as dean of the College of Engineering and director of the Center for Composite Materials from 1977 to 1991. He was appointed Robert L. Spencer Professor of Engineering at the University of Delaware in 1986 in recognition of his outstanding scholarship in the field of composite materials in the subject areas of advanced manufacturing science, durability, design, and characterization. Dr. Pipes is the author of more than 100 archival publications, including four books, and has served on the editorial boards of three journals in his field. He has been recognized for his leadership in creating partnerships for university research with the private sector, government, and academia, and served as one of the first six directors of the National Engineering Research Centers of the National Science Foundation. Dr. Pipes received his Ph.D. in mechanical engineering from the University of Texas and an M.S.E. from Princeton University. He is the recipient of the Gustus L. Larson Award of Pi Tau Sigma and the Chaire Francqui Distinguished Faculty Scholar Award in Belgium. Dr. Pipes was elected to the Royal Swedish Academy of Engineering Sciences in 1993 and holds the rank of fellow in both the American Society of Mechanical Engineers and the Society for the Advancement of Material and Process Engineering. Dr. Pipes has served on a number of National Research Council panels as both a member and chair and served two terms on the National Materials Advisory Board.

WILLIAM HOOVER, *vice chair*, is currently a consultant on aviation, defense, and energy matters. He is the former executive vice president of the Air Transport Association of America, where he represented the interests of the U.S. major airlines industry, particularly in matters related to technical, safety, and security issues. Prior to holding this position, he served as the assistant secretary of defense programs, U.S. Department of Energy, where he was responsible for the U.S. nuclear weapons program, including safety and security. He is also a Major General, USAF (retired) and has held positions of responsibility within NATO, at the Pentagon with the Secretary of the Air Force, and in Vietnam, where he commanded a combat air wing and flew as a fighter pilot. General Hoover is currently chair of the National Research Council's Aeronautics and Space Engineering Board. He holds a B.S. in engineering from the U.S. Naval Academy and an M.S. in aeronautical engineering from the Air Force Institute of Technology.

RAMESH AGARWAL is executive director of the National Institute for Aviation Research at Wichita State University, which conducts research and technology transfer activities for the purpose of advancing the nation's aviation industry, including the general aviation industry. He is also the former chair of the Aerospace Engineering Department, holds the Bloomfield Distinguished Professorship in the College of Engineering, and is senior fellow at the National Institute for Aviation Research. Since receiving a Ph.D. in aeronautical sciences from Stanford University, Dr. Agarwal has conducted both basic and applied research in all aspects of computational fluid dynamics applied to transport and military aircraft, missiles and launch vehicles, and rotorcraft. He is a fellow of the American Institute of Aeronautics and Astronautics, the American Society of Mechanical Engineers, and the American Association for the Advancement of Science.

JACK BLUMENTHAL, NAE, recently retired as assistant director of the TRW Center for Automotive Technology, where he was responsible for the design and manufacture of advanced technologies for use in automobiles, including "smart" air bag/seat belt systems for passenger safety. Prior to holding this position, Dr. Blumenthal was employed by the TRW Defense and Space Sector in a number of functions related to research and the management of research in manufacturing, chemical engineering, catalysis, high-temperature materials, combustion, and rocket propulsion. He received his Ph.D. in chemical engineering from the University of California, Los Angeles, holds 16 U.S. patents, and is the author or co-author of more than 28 publications.

HEINZ GERHARDT is principal engineer and team leader for advanced projects in the Military Aircraft Systems Division of the Northrop Grumman Corporation. In recent years, he was in charge of the design of a high-speed civil transport aircraft achieving increased performance by incorporating a reverse delta wing to attain natural laminar flow. He also has been involved in a study to explore the synergistic benefits of liquid hydrogen for jet fuel and thermal laminar flow control in subsonic, long-range surveillance aircraft. Mr. Gerhardt has worked for Northrop Grumman since 1962 in various research and management positions during which time he developed a number of innovative concepts, including variable span wings, transverse thrust for lift augmentation, and a linear turbine for maglev train propulsion. He graduated with a Diplom-Ingenieur degree (M.S. equivalent) in mechanical engineering from the Technical University, Darmstadt, Germany. He is an associate fellow of the American Institute of Aeronautics and Astronautics, which awarded him the Aerodynamics Award in 1994. Mr. Gerhardt holds 12 patents.

EDWARD GREITZER, NAE, is currently director of Aeromechanical, Chemical, and Fluid Systems at United Technologies Research Center, on leave from the Massachusetts Institute of Technology's (MIT) Department of Aeronautics and Astronautics, where he was associate head. He is also a former director of the MIT Gas Turbine Laboratory. Dr. Greitzer's research at MIT and at Pratt & Whitney (prior to joining the MIT faculty) has focused on fluid dynamics, propulsion, turbomachinery, gas turbine engines, and active control of aeromechanical systems. He is a fellow of the

American Society of Mechanical Engineers and the American Institute of Aeronautics and Astronautics, holds several patents, has authored or co-authored more than 50 publications, and has been a member of the Air Force Scientific Advisory Board and the NASA Aeronautics Advisory Committee. Dr. Greitzer received his undergraduate and graduate degrees in mechanical engineering from Harvard University.

RICHARD GOLASZEWSKI is executive vice president of GRA, Incorporated (formerly Gellman Research Associates), where he specializes in aviation economics, public policy, and safety. He has conducted studies of airports, airlines, aircraft manufacturers, and aviation infrastructure. He also has directed major studies on the appropriate role of government in civil aeronautics research and international competition in civil aircraft manufacturing. Mr. Golaszewski joined GRA in 1977 and holds a B.S. in accounting from La Salle College and an M.P.A. from the Wharton Graduate School of the University of Pennsylvania. He has been a lecturer at both the Wharton School and La Salle College. Mr. Golaszewski is a member of the Economics and Forecasting Committee of the National Research Council's Transportation Research Board and the Economics and Public Policy technical committees of the American Institute of Aeronautics and Astronautics. Currently, he is program vice president of the Transportation Research Forum.

R. JOHN HANSMAN is a professor in the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (MIT), where he is head of the Humans and Automation Division. He also directs the MIT Aeronautical Systems Laboratory and the MIT International Center for Air Transportation. He has been a member of the faculty since receiving an interdisciplinary Ph.D. in physics, meteorology, electrical engineering, and aeronautical engineering from MIT in 1982. Since 1980, Dr. Hansman's research has been focused on a broad range of flight safety topics, from aviation weather hazards, such as icing and windshear, to instrumentation and pilot-vehicle interface issues. He is the author of more than 150 technical publications in these areas and holds five patents. Dr. Hansman also has more than 4,600 hours of flight experience in airplanes, helicopters, and sailplanes.

CHANTAL JOUBERT is the manager of the Aircraft Protection Group in the Advanced Aircraft Programs Division of Phantom Works at Boeing, Long Beach, California (formerly McDonnell Douglas Aerospace). She is responsible for managing advanced transport aircraft design studies through the evaluation of aircraft survivability and protection. Prior to holding this position, Ms. Joubert was deputy program manager for the Aircraft Hardening Program. She has also managed a number of activities related to the design and development of integrated concepts for laminar flow control, propulsion and environmental controls, and advanced design engineering on both subsonic and supersonic commercial transport aircraft. She holds an Sc.B. in mechanical engineering from Brown University and an M.S. in mechanical engineering from California State University, Long Beach.

ANN KARAGOZIAN is a professor in the Department of Mechanical and Aerospace Engineering at the University of California, Los Angeles (UCLA). Her research interests lie in the fluid mechanics of combustion systems, with current emphasis on numerical simulation and experimental interrogation of acoustically driven reacting flows and high-speed combustion systems. Dr. Karagozian is currently a member of the Air Force Scientific Advisory Board and the NASA Aeronautics and Space Transportation Technology Advisory Committee. She was a member of the NASA Federal Laboratory Review Task Force and the Defense Science Study Group and has served on technical panels and committees for the National Research Council, the Environmental Protection Agency, the U.S. Department of Energy, and the National Science Foundation. She is an associate fellow of the American Institute of Aeronautics and Astronautics and in 1987 was the recipient of the TRW-UCLA Excellence in Teaching Award. She received her B.S. in engineering from UCLA and her M.S. and Ph.D. in mechanical engineering from the California Institute of Technology. She is a registered professional mechanical engineer in the state of California.

DONALD L. NIELSON is the director of the Computing and Engineering Sciences Division and the vice president of SRI International, Menlo Park, California. From 1975 to 1984, he was the director of SRI's Telecommunications Sciences Center. Dr. Nielson's expertise is in information technology, including Information transport systems, distributed processing, artificial intelligence-aided language and reasoning systems, terminal systems and human-computer interaction, computer and communications security, information media and standards, telecommunications sciences, and image processing. He has also studied the problems of inserting advanced commercial-off-the-shelf information technology into field deployable military systems. Dr. Nielson has served on a number of government advisory committees and panels on information technology, including the Technical Advisory Committee to the Defense Advanced Research Projects Agency, the Scientific Advisory Board for the Director, Defense Communications Agency, and the Air Force Scientific Advisory Board. He received his Ph.D. in electrical engineering from Stanford University.

ROBERT J. POLUTCHKO recently retired from Lockheed Martin Corporation as an executive officer and the vice president for technical operations, Lockheed Martin Aeronautics Sector. In this position, he was responsible for the technical management and oversight of all Aeronautics Sector programs, including engineering, development, test, operations, and research and development. Prior to this, he was the senior vice president of technical operations for the Martin Marietta Corporation and vice president of technical operations of the Space Group. He has also been president of the Martin Marietta Information Systems Group and vice president and general manager of the Space and Electronics Division in Denver. He is currently serving on the independent NASA Task Force for Cost Assessment and Validation for the International Space Station. Mr. Polutchko is an elected fellow of the American Institute of Aeronautics and Astronautics and received his B.S. and M.S. degrees in aeronautical and astronautical engineering from the Massachusetts Institute of Technology.

MARTIN POZESKY is president of MTP Associates. Since 1994, he has provided technical, management, and strategic consulting services in air traffic control programs encompassing telecommunications, surveillance, automation, weather, navigation, and landing, and avionics systems. Before forming MTP Associates, Mr. Pozesky worked for the Federal Aviation Administration, where he retired as associate administrator of systems engineering and development. He led U.S. efforts to apply GPS satellite technology to aviation and air traffic control and has led global initiatives in air traffic management, aviation systems engineering, planning, program formulation, program management, and systems integration for more than 20 years. He holds a B.S. in electrical engineering from the University of Maryland and an M.S. in engineering and operations research from George Washington University.

RICHARD R. WEISS is currently a consultant in aerospace science and engineering involving launch vehicles and space systems and is a noted expert on rocket propulsion and technology development. Previously, he was deputy director for space launch systems and technology in the Office of the Undersecretary of Defense, Missiles and Space Systems. Prior to that, he served in increasingly responsible positions in the Air Force laboratory system, including chief scientist of the Rocket Propulsion Laboratory, director of the Aeronautics Laboratory, and, after consolidation, Director of the Propulsion Directorate, Phillips Laboratory. Dr. Weiss has been involved in development and transition of advanced technology for the majority of space and missile (both strategic and tactical) systems in the U.S. inventory today, including the space shuttle main engine. He has served on many national and international committees and directed the Technical Panel for the congressionally directed Space Launch Modernization Panel, chaired by Gen. Thomas Moorman. Dr. Weiss has received several awards, including the Air Force Outstanding Civilian Achievement Award and the American Institute of Aeronautics and Astronautics 1994 Wyld Propulsion Award for leadership in developing propulsion technology. Dr. Weiss holds a Ph.D. from Purdue University, an M.S. degree from the University of Southern California in mechanical engineering, and a B.S. degree from the University of Michigan in aeronautical engineering.

TERRENCE WEISSHAAR is a professor in the School of Aeronautics and Astronautics at Purdue University where he teaches aircraft structures, aircraft design, and aeroelasticity. His research has focused on aircraft structural design and optimization, including active control of aeroelastic stability. He has worked in the area of optimally tailored advanced composite structures to control flutter and wing divergence of advanced aircraft and was an early participant in the Defense Advanced Research Projects Agency X-29 Forward Swept Wing Demonstrator Program. Dr. Weisshaar holds a B.S. in mechanical engineering from Northwestern University, an S.M. degree in aeronautics and astronautics from the Massachusetts Institute of Technology, and a Ph.D. in aeronautics and astronautics from Stanford University. He is a fellow of the American Institute of Aeronautics and Astronautics in recognition of his contributions to advanced composites and aeroelasticity and is a current member of the U.S. Air Force Scientific Advisory Board.

PETER WILHELM, NAE, is the director of the Naval Center for Space Technology, where he has led in the development of two upper-stage vehicles that incorporated solid fuel, bipropellant, monopropellant, and cold gas rockets. He also has directed efforts to develop advanced technology to lower space transportation costs. These technologies include advanced propulsion (hybrid, bimodal, and electric), as well as structures, guidance, and mission operations, including reusability. Mr. Wilhelm's involvement in the development of low-cost launch technology began with the initiation of the Sea Launch and Recovery (SEALAR) Program. Mr. Wilhelm has a B.S. in electrical engineering from Purdue University and is a fellow of the American Institute of Aeronautics and Astronautics.

APPENDIX C

Sources of Input to the Committee

PRESENTATIONS

Committee Meeting 1 (September 15–16, 1997), Washington, D.C.

Aeronautics & Space Transportation Technology Enterprise. Robert Whitehead, Associate Administrator for Aeronautics and Space Transportation Technology, NASA OASTT.

Aeronautics & Space Transportation Technology Enterprise. Robert Pearce, Group Lead, Strategy and Planning, NASA OASTT.

Briefing based on the paper: Frontiers of the "Responsibly Imaginable" in (Civilian) Aeronautics. AIAA Paper 98-0001. Dennis Bushnell, Chief Scientist, NASA Langley Research Center.

Space Transportation Technology Working Group Meeting (October 8, 1997), Washington, D.C.

Space Transportation Investment Strategy. Daniel Mulville, Chief Engineer, NASA

Reusable Launch Vehicle Program. Gary Payton, Head, Space Transportation Technology Division, NASA OASTT

NASA Langley Research Center Meeting (November 3–4, 1997), Hampton, Virginia

Langley Overview. Jeremiah Creedon, Director, NASA Langley Research Center Research Center

Systems Studies in Support of the Aeronautics Enterprise. Joe Chambers, NASA Inter-center Systems Analysis Team, NASA Langley Research Center

Overview of Systems Studies of Scenario-Based Vehicles. Joe Chambers, NASA Inter-center Systems Analysis Team, NASA Langley Research Center

Plan for Outcome-Goal-Based System Studies of OASTT Programs. Sam Dollyhigh, Inter-center Systems Analysis Team, NASA Langley Research Center

Current Program Planning Support. Sam Dollyhigh, Inter-center Systems Analysis Team, NASA Langley Research Center

Airframe Systems Base Research Program. Darrel Tenney, Airframe Systems Program Office, NASA Langley Research Center

ReCAT: A NASA Program to Reduce the Cost of Air Travel. NASA Langley Research Center

Civil Transportation Overview. Cindy Lee, Airframe Systems Program Office, NASA Langley Research Center

High Performance Aircraft. James Burley II, High-Performance Aircraft Office, Airframe Systems Program, NASA Langley Research Center

Advanced Subsonic Technology Program. Sam Morello, AST Program, NASA Langley Research Center

Advanced Subsonic Technology Program, Small Aircraft Transportation System R&D. Bruce Holmes, NASA General Aviation Program Office, NASA Langley Research Center

Key Research Thrusts for Access to Space. Delma Freeman, Aerospace Transportation Technology Office, NASA Langley Research Center

OASTT Aviation Safety Program. Michael Lewis, Aviation Safety Program Office, NASA Langley Research Center

High Speed Research Program Overview. Alan Wilhite, High Speed Research Program Office, NASA Langley Research Center

Technology Visions for LaRC: Materials and Structures Research. Mark Shuart, Materials Division, NASA Langley Research Center

Ideas on Revolutionary Aero Technologies. Ajay Kumar, Aero and Gas Dynamics Division, NASA Langley Research Center

Enabling Technology Goals Addressed by These Technologies. Wayne Bryant, Flight Electronics Technology Division, NASA Langley Research Center

Committee Meeting 2 (November 18–19, 1997), Volpe National Transportation Systems Center, Cambridge, Massachusetts

Long-Term Global Aeronautics Needs and Opportunities: Phase II - Potential Breakthrough Technologies and Long-Term R&D Goals. Richard John, Director, Volpe National Transportation Systems Center

Assessment and Analysis of Aviation System Safety. James Hallock, Aviation Safety Division, Volpe National Transportation Systems Center

The Unintended Consequences of the Rapid Adoption of Advanced Technology in Civil Aviation. Donald Sussman, Operator Performance and Safety Analysis Group, Volpe National Transportation Systems Center

Needs and Opportunities for Information Security in the Air Traffic Management System. Robert Wiseman, Volpe National Transportation Systems Center

Traffic Management Research. Richard Wright, Automation Applications Division, Volpe National Transportation Systems Center

Modeling and Impact Assessment of Aviation Noise. Greg Fleming, Safety and Environmental Technology Division, Volpe National Transportation Systems Center

Presentation to the National Research Council, Commission on Engineering and Technical Systems, Aeronautics and Space Engineering Board. John-Paul Clarke, MIT International Center for Air Transportation, Dept. Of Aero/Astro Engineering, Massachusetts Institute of Technology

Software Breakthroughs. Nancy Leveson, University of Washington (visiting the Dept. of Aero/Astro Engineering, Massachusetts Institute of Technology)

Aerospace Information Systems. John Deyst, Dept. of Aero/Astro Engineering, Massachusetts Institute of Technology

A Design Methodology for the Failure and Durability of Composite Structures. Mark Spearing, Paul Lagace, and Hugh McManus, Technology Laboratory for Advanced Composites, Dept. of Aero/Astro Engineering, Massachusetts Institute of Technology

Advanced Structures and Materials Research II: Programs in the Active Materials and Structures Laboratory. Nesbitt Hagood IV, Dept. of Aero/Astro Engineering, Massachusetts Institute of Technology

Potential Breakthrough Technologies, Propulsion Research at the Gas Turbine Laboratory, MIT. A.H. Epstein, I.A. Waitz, Dept. of Aero/Astro Engineering, Massachusetts Institute of Technology.

The Strategic Plan of the Department of Aeronautics & Astronautics. Edward Crawley, Dept. Of Aero/Astro Engineering, Massachusetts Institute of Technology.

The Lean Aircraft Initiative. Earll Murman, Dept. Of Aero/Astro Engineering, Massachusetts Institute of Technology

Aviation Weather and CNS Research. Raymond LaFrey, James Evans, Steven Bussolari, MIT Lincoln Laboratory

CNS/ATM Technology for Air Transportation. Steven Bussolari, MIT Lincoln Laboratory

Draper Lab's Health Monitoring System Algorithms and Applicable MEMS Technologies. Neil Adams, Control and Dynamical Systems Division, Draper Laboratory

Free Flight in an Era of Highly Constrained Resources. Stephan Kolitz, Draper Laboratory

Avionics Technology Requirements for Low Cost Access to Space. Darryl Sargent, Space & Missile Programs, Draper Laboratory

Recommendations for an Honest and Accurate Approach to Truly Low Cost Access to Space. Robert Sackheim, Propulsion & Combustion Center, TRW Space & Electronics Group

SRI/NASA Ames Research Center Meeting (January 19–21, 1998), San Jose, California

The Pace of Innovation/Human-Computer Interaction. Don Nielson, SRI International

GPS Technology: Needs & Capabilities. Earl Blackwell, SRI International

The Challenge of Flight Software: Breakthrough Technologies and Long-Term R&D Goals. John Rushby, SRI International

Boeing (McDonnell Douglas Aerospace) Blended Wing Body Concept. Robert Liebeck, Boeing Long Beach

Boeing Product Options and Considerations. Jean McGrew, Product Development & Technology, Boeing Commercial Airplane Group

Adaptive Active Control of Combustion: Potential Breakthroughs in Performance Enhancement of Aeropropulsion Engines. C.T. Bowman and R.K. Hanson, Dept. of Mechanical Engineering, Stanford University

Development of Diode-Laser Sensors for Aeropropulsion Engine Control. R.K. Hanson, High Temperature Gasdynamics Laboratory, Stanford University

ASTT Stretch Goals: Meeting the Challenge. Robert J. Hansen, Deputy Director for Research, NASA Ames Research Center

Information Technology at NASA: Archimedes and the Computer. Kenneth Ford, Associate Center Director for Information Technology, NASA Ames Research Center

Information Power Grid: How we see the future of Aerospace High Performance Computing and what we're doing about it. Bill Feiereisen, NASA Ames Research Center

Information Systems Directorate. Steve Zornetzer, Information Systems Directorate, NASA Ames Research Center

Intelligent Flight Control. Joseph Totah, Computational Sciences Division, NASA Ames Research Center

Neural Network Based Flight Control: A Vision of the Year 2025. Joseph Totah (Dr. Charles Jorgensen, PI), Computational Sciences Division, NASA Ames Research Center

NASA Air Traffic Management R&D. Michael Dudley, NASA Ames Research Center

Data Collection and Causal Analysis for Aviation Safety: A Vision of Aviation System Monitoring. Irving C. Statler, NASA Ames Research Center

Avionics Technologies in the Next 25 Years. Rudolph Kalafus, Trimble Navigation

GPS, ATM, and Advanced Cockpit Display Research at Stanford University. Andrew K. Barrows (on behalf of Bradford Parkinson, J. David Powel, Per Enge), Dept. of Aero/Astro, Stanford University

Ohio Aerospace Institute Meeting (February 9–11, 1998), Cleveland, Ohio

Introduction to the Space Access Launch System and Development. Steve Wurst, Space Access LLC

Space Operations Vehicles Technical Background for the National Research Council. Terry Phillips (Lt. Col. Jess Sponable), Air Force Research Laboratory/VTX, Kirtland AFB

Advanced Hypersonic Concepts. Robert Mercier and Tom Curran, Wright Patterson AFB

NASA Lewis Presentations. Carol Russo, et.al.

NASA Marshall Presentations to the Air and Launch Vehicle Technology Meeting. Garry Lyles, et. al.

Future Spacelift Requirements Study Summary. Rex McWaters (R.F. Johnson), The Aerospace Corporation

Pratt & Whitney Advanced Propulsion Concepts. L.L. Coons, Vice President, Engineering, Pratt & Whitney

Long-Range Research in Rocket Propulsion. Pat Carrick, Air Force Research Lab, Rocket Propulsion Directorate

VentureStar: A Revolutionary Space Transportation Launch System. Bob Baumgartner, Lockheed Martin Skunk Works

Kelley Aerospace Eclipse RLV Concept Richard P. Hora, President and CEO, Eclipse Space Lines

DOCUMENTS AND PUBLICATIONS

AGATE Program Folder (Reference Material including: *The AGATE Flier; NASA Facts;* NASA Technical Memorandum 110271, *(Re)inventing Government-Industry R&D Collaboration,* Bruce J. Holmes, Langley Research Center, Hampton, VA, August 1996.)

Brewer, G.D., G. Wittlin, E.F. Versaw, R. Parmley, R. Cima, E.G. Walther. 1981. Assessment of Crash Fire Hazard of LH2-Fueled Aircraft. NASA CR-165525. Washington, D.C.: National Aeronautics and Space Administration.

Burnham, David and Hallock, James. Wake Vortex Separation Standards: Analysis Methods. U.S. Department of Transportation, Federal Aviation Administration, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center, DOT/FAA/ND-97-4, Office of Communications, Navigation, and Surveillance Systems, Washington, D.C. 20591. Final Report, May 1997.

Bushnell, D.M. 1998. Frontiers of the "Responsibly Imaginable" in (Civilian) Aeronautics, AIAA paper 98-0001. Reston, Virginia: American Institute of Aeronautics and Astronautics.

Dawson, Terry. 1994. Perspectives on U.S. Space Launch Systems. A Staff Background Paper. Washington, D.C.: Subcommittee on Space, Committee on Science, Space and Technology, U.S. House of Representatives

Deyst, J.J. 1997. Aerospace Information Systems. Presentation to the Committee to Identify Potential Breakthrough Technologies and Assess Long-term R&D Goals in Aeronautics and Space Transportation Technology, Cambridge, Massachusetts, November 18, 1997.

Devere, T. 1998. E-mail to the Committee to Identify Potential Breakthrough Technologies and Assess Long-term R&D Goals in Aeronautics and Space Transportation Technology from Taft Devere, U.S. Space Command, June 12, 1998.

Dillon, A.C., K.M. Jones, T.A. Bekkedahl, C.H. Klang, D.S. Bethune, and M.J. Heben. 1997. Storage of hydrogen in single-walled carbon nanotubes. Nature 386 (Mar 27): 377–379.

Endsley, M.R. and M.D. Rodgers. 1994. Situation Awareness Information Requirements for En Route Air Traffic Control, Final Report. DOT/FAA/AM-94/27. Washington, D.C.: Federal Aviation Administration.

Epstein, A., and I. Waitz. 1997. Potential Breakthrough Technologies, Propulsion Research at the Gas Turbine Laboratory, MIT. Presentation to the Committee to Identify Potential Breakthrough Technologies and Assess Long-term R&D Goals in Aeronautics and Space Transportation Technology, Cambridge, Massachusetts, November 18, 1997.

Epstein, A.H. and S.D. Senturia. 1997. Macro Power from Micro Machinery, Science Magazine, 276: 1211

Fact Sheet. National Space Policy. The White House, Office of Science and Technology Policy, September 19, 1996.

Fitts, P.M. 1951. Human Engineering for an Effective Air Navigation and Traffic Control System. Washington, D.C.: National Research Council.

Free Flight. 1998. FAA Free Flight World Wide Web site, www.faa.gov/freeflight

Galbraith, A.D. 1996. Electric Propulsion for Light aircraft: Lithium-Air Fuel Cell for Primary Power. NIAR 96-3. Witchita, Kansas.: National Institute for Aviation Research, Wichita State University.

Gartz, Paul Ebner. 1996. Commercial Systems Development in a Changed World - The Engineering of Large Commercial Jet Transports. Paper originally prepared for the IEEE/INCOSE Joint Technical Journal (no volume, issue, page numbers, or exact title provided).

Gartz, Paul Ebner. 1997. Does Aerospace Technology Have a Future in Aerospace? Paper Adapted by author from IEEE Spectrum Magazine article, Technology Update issue, January 1998.

Gore, Al. 1997. Final report to President Clinton, White House Commission on Aviation Safety and Security, February 12, 1997. Washington, D.C.: Office of the Vice President of the United States

GRA. 1992. Economic Analysis of Aeronautical Research and Technology—An Update. Jenkintown, PA: GRA, Inc.

Information Technology at NASA: Accepting the Challenge of Excellence (Brochure).

Lefebrve, A.H. 1995. The Role of Fuel Preparation in Low-Emission Combustion. Journal of Engineering for Gas Turbines and Power. 117(4): 617–654.

Leveson, Nancy. 1992. High Pressure Steam Engines and Computer Software., Paper presented at the International Conference on Software Engineering, Melbourne, Australia, May 1992 (in proceedings)

Leveson, Nancy. 1995. Embedded Computer Systems Initiative: A Response to the 1995 CIC Draft Report. White Paper for the ARPA Workshop on the CIC Draft Report, July 1995

Leveson, Nancy. 1997. The Impact of Digital Computers on Engineering Practice. Paper for the NAE Workshop on the Changing Nature of Engineering Practice, November, 1997

Liebeck, R.H., M.A. Page, and B.K. Rawdon. 1998. Blended-Wing Body Subsonic Commercial Transport. AIAA-98-0438. Reston, Virginia.: American Institute of Aeronautics and Astronautics.

Littlewood, B. and L. Strigini. 1993. Validation of Ultrahigh Dependability for Software-Based Systems. Communications of the ACM, 36(11).

NASA (National Aeronautics and Space Administration). 1995. Achieving Aeronautics Leadership—Aeronautics Strategic Enterprise Plan, 1995–2000. Washington, D.C.: National Aeronautics and Space Administration.

NASA. 1996. (Re)inventing Government-Industry R&D Collaboration. NASA Technical Memorandum 110271, Bruce J. Holmes. Hampton, VA: NASA Langley Research Center Research Center.

NASA. 1997. Aeronautics & Space Transportation Technology: Three Pillars for Success. Office of Aeronautics and Space Transportation Technology, Alliance Development Office. Washington, D.C.: National Aeronautics and Space Administration.

NAE (National Academy of Engineering). 1988. Cities and Their Vital Infrastructure: Past, Present, and Future. Washington, D.C.: National Academy Press

NRC (National Research Council). 1995. Reusable Launch Vehicle Technology Development and Test Program. Aeronautics and Space Engineering Board, Committee on Reusable Launch Vehicle Technology and Test Program. Washington, D.C.: National Academy Press.

NRC. 1997. Aircraft Noise Modeling. Transportation Research Circular, Number 473. Washington, D.C.: Transportation Research Board, National Research Council.

NRC. 1997. Maintaining U.S. Leadership in Aeronautics—Scenario-Based Strategic Planning for NASA's Aeronautics Enterprise. Aeronautics and Space Engineering Board, Steering Committee for a Workshop to Develop Long-Term Global Aeronautics Scenarios. Washington, D.C.: National Academy Press.

NSTC (National Science and Technology Council). 1995. Goals for a National Partnership in Aeronautics Research and Technology. Executive Office of the President, Office of Science and Technology Policy. Washington, D.C.: National Science and Technology Council.

OSTP (Office of Science and Technology Policy). 1985. National Aeronautical R&D Goals—Technology for America's Future. Executive Office of the President. Washington, D.C.: Office of Science and Technology Policy.

OSTP. 1987. National Aeronautical R&D Goals—Agenda for Achievement. Executive Office of the President. Washington, D.C.: Office of Science and Technology Policy.

Proceedings of the Symposium on Enabling Technologies for Advanced Transportation Systems. Held on September 16-18, 1997, Cambridge, MA, U.S. DOT Research and Special Programs, Volpe National Transportation Systems Center, November 19, 1997.

Rogers, R.L. 1989. A Knowledge-Based Tool for Multilevel Decomposition of a Complex Design Problem. NASA TP2903. Washington, D.C.: National Aeronautics and Space Administration.

Rosen, K. M. 1997. Memo to the Committee to Identify Potential Breakthrough Technologies and Assess Long-term R&D Goals in Aeronautics and Space Transportation Technology, United Technologies, Sikorsky Aircraft, November 5, 1997.

Sokolowski, Daniel E. 1997. Toward Air Transportation in 2020: Aeronautical and Aeropropulsion Ideas. Cleveland, Ohio: Aeronautics Directorate, NASA Lewis Research Center

Statement on National Space Transportation Policy. The White House, Office of Science and Technology Policy, August 5, 1994.

The Aerospace Corporation. 1997. Future Spacelift Requirements Study. Prepared by the Aerospace Corporation Study Team for NASA Marshall Space Flight Center and Air Force Space Command Headquarters, ATR-97(2157)-1.

The Lean Aircraft Initiative: Making a Measurable Difference (Program Folder)

Vakil, Sanjay S. and R. John Hansman. 1998. Functional Models of Flight Automation Systems to Support Design, Certification, and Operation, AIAA 98-1035. Paper presented at the 36th Aerospace Sciences Meeting & Exhibit, January 12-15, 1998, Reno, NV.

APPENDIX D

Complete List of Technologies Assessed

AIR VEHICLE TECHNOLOGY

Propulsion Technologies

- active, closed-loop engine control with real-time, detailed diagnostics
- actively controlled combustor pattern factor
- advanced combustor cases
- advanced membrane technology
- advanced propulsion systems
- advanced propulsion systems for rotorcraft
- aircraft turbine core engines with oxygen-enriched airstream
- aircraft turbine engine with thrust modulation and/or vectoring
- alternate fuels and propulsion systems
- alternative propulsion for small airplanes
- aspirated compressors
- condition-based monitoring/maintenance
- cooled cooling air
- electrically powered aircraft wheels
- fine spray grid fuel-air injection
- fuel reforming/fuel cells
- integral heat exchanger
- integrated combustor front-end design
- intelligent gas turbine engines
- large turndown ratio combustors
- low cost turbines for general aviation and helicopters

- low or no emission engines
- nacelle boundary layer suction
- nonmetallic aircraft turbine engines
- revolutionary combustors
- trapped vortex pilot zone
- turbo-electric hybrid powered aircraft
- turbogenerators

Aerodynamics

- elimination of airframe wave drag through wave cancellation
- maintaining laminar flow on airframes by means of surface cooling
- minimum-wake wing
- technology to extract the rotary energy of wingtip vortices

Air Vehicle Configurations

- "electraircraft" x-plane
- "green" aircraft configurations and operations
- air vehicles optimized for reduced operating costs
- blended-wing body (BWB)
- high speed civil transports
- mid-wing twin fuselage
- O-plane
- practical, affordable flying automobile
- strut-braced wing
- unconventional aircraft
- unpiloted air vehicles
- V/STOL aircraft to enhance capacity
- variable diameter tiltrotors
- vertical flight for commercial applications
- vertical flight for personal transportation

- very large cargo aircraft
- Z plane

Control Systems and Sensors

- aircraft mounted remote weather sensors
- control systems
- data fusion/estimation
- low-cost ice protection systems and ice avoidance capability
- noise reduction technology
- photonics-based sensors

Structures, Materials, and MEMS

- "smart systems" applications
- advanced materials
- aluminum/aluminum diboride metal matrix composites
- carbon nanofibers with an ultra high capacity to absorb/adsorb hydrogen gas at ambient temperatures and modest pressures
- carbon/carbon/boron nitride composites
- laminated structures technology
- materials and materials processing
- MEMS in-situ cooling of hot section sensors
- micro electromechanical systems (MEMS)
- miniaturization, smart structures, and health-monitoring
- multichip module laminates
- nanoporous composite fiber activated carbon assemblies
- new alloys
- recyclable copolyester thermosets
- reinforced composites for propulsion systems
- shaped/smart materials

- superconducting electronic materials
- very low cost composites
- wing sealants

Design and Manufacturing

- automated assembly
- fabrication by light
- integrated design
- lean manufacturing for gas turbine engines
- modeling and simulation
- new methodology for engine design and development
- virtual manufacturing
- virtual prototyping
- virtual test cells

AIR TRANSPORTATION SYSTEM TECHNOLOGY

Flight Deck and Human/Automation Systems

- affordable, reliable fly-by-light control systems
- automated preflight procedures
- automated reasoning
- care free handling
- configuration performance monitoring and situation awareness
- decision aids
- distributed systems (via datalinks)
- flight deck workload reduction technology
- highly capable automation systems
- human-machine systems (cognitive engineering)
- integrated flight systems
- situation awareness alerting systems

- technology for uncrewed aircraft
- upwardly compatible systems
- virtual visual meteorological conditions (VMC)

Communications, Navigation, Surveillance, and Air Traffic Management

- 4-D operations (four dimensional precision trajectory prediction)
- air traffic control
- air traffic management for V/STOL aircraft
- antijamming technology
- free flight and a precise knowledge of location
- high altitude airborne communications platforms
- information security
- low cost inertial measurement units
- reliable and confirmed ATC information in the cockpit
- satellite-based communications, navigation, and surveillance systems

Terminal Area Technologies

- energy absorbing runways
- formation landings
- high speed turnoffs
- V/STOL infrastructure
- wake vortex mitigation
- wide runways

Software and Process Technologies

- autocode
- certification
- common conceptual model for software
- formal methods for software development

- improved theory and methods of risk estimation and management in complex flight-critical systems
- new software verification and validation processes
- next generation "goal level" autonomy algorithms
- predictive tools/models for analyzing the total air transportation system
- safety analysis
- software architecture
- software certification
- software designed for evolution

SPACE TRANSPORTATION TECHNOLOGY

Propulsion Technologies

- advanced fuels
- advanced high energy propellants
- blast wave accelerator
- combined cycle rocket-based engines
- endothermic hydrocarbons
- high efficiency H_2-O_2 rocket engine capable of providing optimum expansion ratio performance over the ambient pressure range from 1 atmosphere to space vacuum
- hydrogen densification/storage
- increased thrust-to-weight engine
- laser propulsion
- liquid air, cooled air propulsion concepts
- pulse detonation engine
- reformed hydrocarbons
- solid/metallic hydrogen
- strained ring hydrocarbons
- unique propulsion concepts
- variable expansion ratio engine

Launch Vehicle Configurations and Components

- advanced composite materials
- advanced thermal protection systems
- cost optimized multistage to orbit rocket
- integrated thermostructural systems
- lightweight and high performance components for reusable launch vehicles
- lightweight structures
- miniaturization

Launch Assist Technology

- air launch systems
- cannons
- magnetic lifter

Ground Infrastructure

- modeling and simulations of operations
- prelaunch processing
- test and mission planning automation

Mitigation of Environmental Impact

- noise control technology
- pollution reduction technology

APPENDIX E

Workshop on Breakthrough Aerospace Technologies

The Committee to Identify Potential Breakthrough Technologies and Assess Long-Term R&D Goals in Aeronautics and Space Transportation Technology held a workshop at the National Research Council's Cecil and Ida Green Building in Washington, D.C., on February 19 and 20, 1998. The participants are listed below:

Howard Aylesworth, Jr., Aerospace Industries Association of America

M. Craig Beard, Consultant

James Berry, Boeing Advanced Space Systems, Huntington Beach

Larry Bober, NASA Lewis Research Center

Dennis Bushnell, NASA Langley Research Center

John Cole, NASA Marshall Space Flight Center

Eugene Covert, Massachusetts Institute of Technology, Emeritus

Edward "Tom" Curran, Air Force Research Lab, Wright Patterson AFB

Paul Czysz, Parks College, St. Louis University

James Economy, University of Illinois at Urbana-Champaign

Roger Fleming, Air Transport Association (retired)

William Fromme, ARINC

Robert Hanson, NASA Ames Research Center

Keith Kedward, University of California, Santa Barbara

Emmett Kraus, Cessna Aircraft

Stephen McBrien, The MITRE Corporation

Robert Moffitt, Sikorsky Aircraft

Charles Saff, Phantom Works, The Boeing Company, St. Louis

Robert Schwab, The Boeing Company, Seattle

John Staples, Department of Transportation, Federal Aviation Administration

Ben Zinn, Georgia Institute of Technology