National Plan for Aeronautics Research and Development and Related Infrastructure

December 2007

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EXECUTIVE OFFICE OF THE PRESIDENT
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
WASHINGTON, D.C. 20502

January 10, 2008

Dear Colleague:

This National Plan for Aeronautics Research and Development and Related Infrastructure (the "Plan") was developed in response to Executive Order 13419, which implemented the National Aeronautics R&D Policy and called for a plan for national aeronautics R&D and for related infrastructure. This Plan establishes high-priority national aeronautics research and development (R&D) challenges, goals and supporting objectives to guide the conduct of U.S. aeronautics R&D activities through 2020.

This Plan is timely in light of President Bush's recent actions to reduce air traffic congestion and flight delays. The Plan complements those nearer-term efforts by addressing the longer term research needed to support U.S. aeronautics development through 2020 and transform the nation's air transportation system.

Following the structure of the Principles of National Aeronautics R&D Policy, this Plan establishes aeronautics R&D goals and supporting objectives with timelines, as well as guidance outlining the path forward for developing an aeronautics research, development, test and evaluation infrastructure plan. Research and development priorities are aligned with the Policy Principles of Mobility, National Security and Homeland Defense, Safety, and Energy and Environment. Consistent with Executive Order 13419, updates to this Plan will be provided every two years.

By coordinating a common planning focus for the departments and agencies to define and achieve high priority national goals and objectives, we will help ensure that our Nation sustains the technical leadership in aeronautics that is essential to America's economic success and the protection of America's security interests at home and around the globe.

Sincerely,

John H. Marburger, III
Director, Office of Science and Technology Policy

National Plan for Aeronautics Research and Development and Related Infrastructure

December 2007

Aeronautics Science and Technology Subcommittee
Committee on Technology
National Science and Technology Council

Table of Contents

Table of Contents Continued

OVERVIEW

On December 20, 2006, Executive Order 13419, "National Aeronautics Research and Development," established the nation's first policy to guide Federal aeronautics R&D through 2020. The Executive Order stated, "Continued progress in aeronautics, the science of flight, is essential to America's economic success and the protection of America's security interests at home and around the globe" and called for a plan for national aeronautics research and development (R&D) and for related infrastructure.[1]

Executive Order 13419 was supported by an accompanying Policy, the National Aeronautics R&D Policy, which provided further guidance for such an R&D plan.[2] The Policy called for an R&D plan "comprising national research priorities and objectives, roadmaps to achieve the identified objectives, and timelines." In addition, the Policy called for an infrastructure plan for managing critical Federal research, development, test and evaluation (RDT&E) assets and stated that the infrastructure plan should "identify which assets are considered critical from a national perspective and define an approach for constructing, maintaining, modifying, or terminating these assets based on the needs of the broad user community."

This National Plan for Aeronautics Research and Development and Related Infrastructure ("Plan"), which will be reviewed on a biennial basis, answers the Executive Order and Policy by providing the nation's first integrated plan that the Federal aeronautics R&D enterprise should pursue for both R&D and related infrastructure. In addition, the Plan lays out further implementation actions that will meet the full intent of the Policy.

The National Aeronautics R&D Policy laid out seven key Principles to guide the conduct of the nation's aeronautics R&D activities through 2020. These Principles, with two exceptions noted below, serve as the framework for this Plan:

- Mobility through the air is vital to economic stability, growth, and security as a nation.
- Aviation is vital to national security and homeland defense.
- Aviation safety is paramount.
- Security of and within the aeronautics enterprise must be maintained.
- The United States should continue to possess, rely on, and develop its world-class aeronautics workforce.
- Assuring energy availability and efficiency is central to the growth of the aeronautics enterprise.
- The environment must be protected while sustaining growth in air transportation.[3]

1 http://www.ostp.gov/nstc/aeroplans/pdf/aerordEO12_20_06final.pdf.
2 http://www.ostp.gov/nstc/html/NationalAeronauticsRDPolicy06.pdf.
3 Energy and Environment were separate Principles in the Policy; however, they are sufficiently integrated that they are considered together in this Plan.

For each Principle addressed in this Plan, a description of the state of the art of related technologies and systems is provided. A set of fundamental challenges and associated high-priority R&D goals that seek to address these challenges follows. To give additional clarity and definition, the Plan provides supporting objectives for each goal. These objectives are phased over three time periods: near term (<5 years), mid term (5–10 years), and far term (>10 years).

Note that two Principles in the Policy will be addressed in different venues. Aviation security R&D efforts are coordinated through the National Strategy for Aviation Security and its supporting plans. Such R&D encompasses a wide array of areas including: personnel, baggage and cargo screening; infrastructure protection; cyber security; and aircraft protection technologies. Aerospace workforce issues are being explored by the Aerospace Revitalization Task Force led by the Department of Labor pursuant to Public Law 109-420.

The challenges, goals, and objectives contained in this document were identified through the consensus of the departments and agencies on the Aeronautics Science & Technology Subcommittee of the National Science and Technology Council, with input from the broader community and non-Federal stakeholders, as well as recent studies on aeronautics such as the National Research Council's *Decadal Survey of Civil Aeronautics*.[4] The members of the Aeronautics Science & Technology Subcommittee involved in the creation of this Plan included representatives from the Departments of Commerce, Defense, Energy, Homeland Security, State, and Transportation, as well as from several Federal agencies and offices, including the Environmental Protection Agency, the Federal Aviation Administration, the Joint Planning and Development Office, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and the National Science Foundation.

The goals and objectives for each Principle in this Plan are considered the highest priority and are intended to provide high-level guidance for foundational, advanced aircraft systems, and air transportation management systems R&D through 2020. While the challenges, goals, and objectives are organized by the Principles outlined above, most of the R&D goals and objectives will require stable and long-term foundational research across a breadth of aeronautics disciplines to provide the underlying basis for new technological advances and breakthroughs. Such foundational research is often cross-cutting, resulting in technology advances that have applications across several Principles. Moreover, new ideas and technologies that are generated by foundational research will help inform future updates to this Plan.

4 http://www.nap.edu/catalog.php?record_id=11664

These goals and objectives are not intended to endorse specific technologies or assign priorities to research areas within those Principles. It is important to quantify the progress toward achieving these goals and objectives to the greatest possible extent. Hence, where possible, appropriate metrics have been developed and baseline values have been defined. In accordance with guidance provided within the Executive Order and the National Aeronautics R&D Policy, the goals and objectives will be reviewed at two-year intervals. As part of the biennial review process, these metrics and baseline values will be re-evaluated and re-baselined as needed. It must be stressed that in addition to these goals and objectives, departments and agencies have mission-specific and unique R&D activities that may not have been prioritized for this interagency national Plan; however, their exclusion does not diminish their importance or the need to pursue them.

This Plan also outlines the path forward for developing the RDT&E infrastructure plan that will focus on the critical RDT&E assets and capabilities necessary to support the aeronautics R&D goals and objectives laid forth in this Plan. The RDT&E infrastructure includes experimental facilities and computational resources, as well as the cyber-infrastructure that serves to connect the two. This infrastructure plan will also address an approach for constructing, maintaining, modifying, or terminating assets based on the needs of the broad user community.

The goals and objectives in this Plan will serve as the basis for a supplemental National Science and Technology Council aeronautics R&D report and a plan for aeronautics RDT&E infrastructure that are called for in this Plan.

MOBILITY THROUGH THE AIR IS VITAL TO ECONOMIC STABILITY, GROWTH, AND SECURITY AS A NATION

Providing for mobility requires an aeronautics enterprise with sufficient capacity to meet increasing demand for air travel and transport and with sufficient flexibility and affordability to accommodate the full range of aircraft requirements and attributes. Possessing the capability to move goods and people, point-to-point, anywhere in the nation and around the world is essential to advance the local, state, and national economies of the United States. Furthermore, the United States, in cooperation with international partners, should play a leading role in ensuring global interoperability.

INTRODUCTION

Mobility through the air is a key function of the nation's air transportation system. The U.S. economic system revolves around the capability to move goods and people efficiently throughout the United States and the world. This requires an aeronautics enterprise with sufficient flexibility and affordability to accommodate the full range of aircraft requirements and attributes, as well as projected passenger and cargo traffic.

Due to increases in commercial air travel and the recovery and growth of the general aviation industry, the capacity of the National Airspace System (NAS) needs to accommodate, according to estimates, between two and three times the number of operations by 2025 (where operations are defined as takeoffs and landings) as it did in 2004.[5] The environment where the NAS must accommodate three times the number of operations is referred to as the "3× environment." In addition, the general aviation fleet is forecast to grow more than 20% during the next 10 to 15 years, and increased operations involving very light jets, uncrewed aircraft systems (UAS), rotorcraft, and suborbital space vehicles are possible. By 2025, the possibility exists that new aircraft with significant changes in their performance capabilities will join the fleet (e.g., blended-wing body aircraft, supersonic business jets and small transports, and advanced rotorcraft). Finally, the future NAS must be able to accommodate and integrate various operational needs for aviation security, as well as national security and homeland defense.

At present, however, there are clear signs that the nation's air traffic management system is under serious stress as a result of current demand levels. The system is extremely sensitive to local perturbations and reacts with system-wide ripple effects. Delays result in a huge cost to industry, passengers, shippers, and government. The growth in air transportation has also triggered community concerns over aircraft noise, air quality, and congestion. Many market-based, economic solutions could be pursued to reduce congestion, such as

5 Commercial enplanements are forecast to grow by factors ranging from 1.8 to 2.4 times 2004 levels by 2025 (FAA 2004 Terminal Area Forecast; Boeing 2004 Commercial Market Outlook; Sherry Borener et al., "Can NextGen Meet the Demands for the Future?" *The Journal of Air Traffic Control*, Jan–Mar 2006). This translates into operations growing by factors from 1.4 (with an average increase of 10+ passengers per flight) to 3.0 (with a shift of 2% of passengers to Very Light Jets) (Borener 2006).

implementing congestion pricing or developing an alternative to first-come-first-served service. These have not been fully explored yet. Despite these potential nearer term solutions, current demand predictions still point to the need for a fundamental transformation of the NAS for long-term growth, which is the focus of the R&D recommendations in this section.

A mandate for the design and deployment of a transformed air transportation system was established in *Vision 100 – Century of Aviation Reauthorization Act* (Public Law 108-176).[6] The law established a Joint Planning and Development Office (JPDO) representing six government departments and agencies and the private sector to develop the Next Generation Air Transportation System (NextGen – formerly referred to as NGATS). NextGen will entail a revolutionary transformation of the U.S. airspace system to a performance-based, scalable, network-enabled system that will be flexible to adapt to meet future needs. Achieving NextGen will require focused and coordinated R&D to address key decisions and challenges associated with system transformation.

In the sections on mobility and energy and environment, this document will refer to future generations of advanced aircraft with enhanced capabilities using the following notation:

- "N" refers to the current generation of tube-and-wing aircraft entering into service in the year 2008 (the Boeing 787 is a representative example).
- "N+1" represents the next generation of tube-and-wing aircraft with entry into service, market permitting, around 2015.
- "N+2" refers to advanced aircraft in the generation after N+1, which are likely to use revolutionary configurations (such as hybrid wing-body, small supersonic jets, cruise-efficient short take-off and landing and advanced rotorcraft) and are expected to enter into service, market permitting, in the 2020–2025 time frame (initially with potentially military or cargo applications).
- "N+3" refers to the generation of aircraft after N+2, which have dramatically improved performance and reduced noise and emissions and are expected to enter into service in the 2030–2035 period.

STATE OF THE ART

Today's aircraft operate with inefficient procedures that are very similar to those created over 30 years ago. The NAS is a large, complex, distributed, and loosely integrated network of systems, procedures, and infrastructure, much of it decades old. Air traffic control is performed primarily through the use of surveillance radars, voice radio systems, limited computer support systems, and numerous complex procedures. The NAS's operating procedures were originally designed around technologies now considered antiquated, yet

6 http://www.jpdo.gov/vision_100_law.asp.

these procedures remain largely unchanged despite new concepts of operation afforded by current and near-term technologies.

The resulting inefficiencies pose severe cost and capacity limitations on aviation growth. Uncertainties in the total flight environment negatively affect system throughput. Uncertainty is managed by queuing traffic to be serviced, and demand is managed by restricting access to the airspace to avoid straining capacity. On the airport surface, runway incursions and missed taxi clearances result from a lack of situational awareness and communication limitations for operators or traffic controllers.

FUNDAMENTAL MOBILITY CHALLENGES TO OVERCOME

Shortfalls associated with the state of the art will have to be overcome to achieve mobility during the decades ahead. The following are major challenges:

- Reducing separation distances between aircraft to increase traffic density and determining functions that can be moved to the cockpit to improve operations without compromising safety.
- Dynamically balancing airspace capacity to meet demand by allocating airspace resources and reducing adverse impacts associated with weather.
- Developing more accurate and timely observations and forecasts of aviation-relevant weather to enable NextGen.
- Increasing airport approach, surface, and departure capacity.
- Developing airport terminal designs that facilitate passenger throughput, including movement between surface and air transportation modes.
- Introducing new generations of air vehicles including rotorcraft with vastly improved performance and revolutionary capabilities such as shorter takeoff and landing, faster (supersonic) speeds, and larger passenger and cargo capacity, while also achieving significantly reduced environmental impact.
- Improving the efficiency and performance of all classes of aircraft to take advantage of improved methods of operating aircraft within the NAS.
- Defining appropriate roles for humans (notably air traffic controllers and pilots) in relation to automation, and developing automation that humans can reliably and fluidly interact with, monitor, and, when appropriate, override.
- Understanding enterprise-level issues (e.g., environmental, organizational) and interactions critical to successful transformation.

MOBILITY R&D GOALS AND OBJECTIVES

The future vision for air transportation calls for a system-wide transformation leading to an enhanced set of system capabilities. These include communication and physical

infrastructure, the acceleration of automation and procedural changes based on four-dimensional (space and time) trajectory analyses, dynamic reconfiguration and reallocation of the airspace to be scalable to geographic and temporal demand, and an aircraft fleet designed to leverage these enhancements. Addressing the major challenges to this system-wide transformation requires achieving the five key goals and associated time-phased objectives listed below. However, this does not imply that focused research associated with the mobility goals and objectives alone is sufficient. Foundational research provides the "building blocks" of a technology base to successfully address the stated goals and objectives. Hence, complementary foundational aeronautical research efforts are also required in areas such as guidance, navigation, and control; fluid mechanics; advanced structures and materials; airframe/propulsion system integration; and advanced mathematics, statistics, computational science, and optimization techniques.

Another major challenge will be to define the proper balance in responsibility between humans and automation. Research into the human-machine relationship does not appear as a set of separate research topics in the mobility goals and objectives table because it must be an integral part of research to define the details of new operational capabilities identified in Goals 1–4. Human-machine integration efforts are also identified in the national security and safety sections.

Note, for the purposes of the mobility goals and objectives, "enable" means to advance the development of technologies or systems to levels that appropriately facilitate eventual industry uptake for commercial applications; fleet insertion will add to the time line.

Goal 1—Develop reduced aircraft separation in trajectory– and performance-based operations (see p. 41)

Reduced aircraft separation will require a move to trajectory-based operations, performance-based navigation, and a paradigm shift in control with new allocation of responsibilities between air and ground and between humans and automation. At the core of the paradigm shift is focused research on aircraft trajectories. Research into trajectory prediction, synthesis, and uncertainty is an enabler for separation assurance, dynamic airspace configuration, and traffic flow management for both current operations and future super density operations across all flight domains.

Performance-based navigation provides a basis for the design of automated flight paths, airspace design, aircraft separation, and obstacle clearance and defines how an aircraft will execute a trajectory. Research into candidate concepts of operations and enabling technologies is needed for a shift in separation responsibility from ground controllers to the cockpit. Technologies supporting positioning, navigation and timing capabilities are key

enablers for separation management. Developing enhanced positioning, navigation and timing capabilities, including identifying feasible backups, is a critical research focus. This research must investigate a means to take advantage of existing and future avionics capabilities to expand: (1) the rapidly growing set of applications such as Automatic Dependent Surveillance-Broadcast; and (2) area navigation and required navigation performance in the terminal and en-route environments. The research must also investigate impacts to pilot and controller (and other vital personnel, such as airline operators and remote aircraft operators) workload, and roles and responsibilities for automated route clearances. Another major research challenge is to define the proper balance in responsibility between the ground and the cockpit. Finally, this research must support the definition of new separation standards, procedures for trajectory-based operations, and certification of new ground- and cockpit-based systems, including the development of safety risk-management analyses.

Goal 2—Develop increased NAS capacity by managing NAS resources and air traffic flow contingencies (see p. 41)

As demand grows, enhanced traffic management techniques based on four-dimensional aircraft trajectory updates that take weather and other airspace resources and constraints into account will be required in order to balance NAS capacity to future demand. A basic underlying tenet will seek to maximize operators' opportunities to use the system rather than to constrain flight demand. Enhanced flight plan negotiations and improved situational awareness are necessary to accommodate operators' preferences and impose restrictions only where necessary. System capacity increases are sought by dynamically restructuring the airspace, by dynamically allocating system resources (including people), and by promptly communicating system status to all users. Research is required to identify flexible airspace structures, including boundaries, trajectory predictions, routes, or performance requirements, that can be dynamically adjusted to meet demand.

The needs of both military and civilian operators will be balanced through enhanced solutions for effective airspace utilization. This requires research focused on advanced concepts for collaborative air traffic management. Dynamic adjustments of airspace configurations to meet demand must interact with a traffic flow management function, and this interaction will be on multiple temporal scales: annual, seasonal, monthly, weekly, and daily. Because the future traffic demand is expected to have a diverse fleet mix and a broader mix of operators, new traffic flow management concepts must be developed. The complex interaction between the separation management function and the traffic flow management function must be researched to understand the level of allowable traffic complexity in the design of traffic flows. In addition, high-density traffic flows especially need to be robust during off-nominal conditions, such as when an aircraft deviates from its assigned trajectory. This may require a balance between eliminating all predictable sources of variation in traffic spacing versus maintaining sufficient separation in the traffic flows to adjust for

unexpected circumstances. Research supporting the development of traffic flow models to systematically assess advanced concepts is also required to advance this goal.

Goal 3—Reduce the adverse impacts of weather on air traffic management decisions (see p. 41)

A key component of traffic flow management research will be to understand uncertainties due to weather. A common weather picture (shared situational awareness) of forecasts and observations from which all weather-related decisions can be made is needed. Research must determine the spatial and temporal resolution and accuracy required to integrate weather information with air traffic management automation systems. Focused research is necessary to develop real-time verification systems that quantitatively assess the accuracy and reliability of probabilistic weather forecasts. This includes generation of the following aviation weather parameters: convection, winter storms, icing, turbulence, ceiling, and visibility. A key concept to facilitate this goal is the NextGen Network Enabled Weather virtual database capability. With NextGen Network Enabled Weather capabilities, observations and forecasts will be arbitrated and merged into a single authoritative source of weather information used in joint government/user NextGen decision-making processes. This research is an important precursor to enhanced situational awareness (in particular enhanced flight deck displays of weather conditions and forecasts) discussed in Goal 2 in the aviation safety section. Focused research is also required to understand the disparate interpretations of this single authoritative source of weather information by all stakeholders, and their impact on decision-making processes.

Goal 4—Maximize arrivals and departures at airports and in metroplex areas (see p. 41)

Throughput in high-density, complex terminal airspace is currently limited by several factors. Procedures designed around now-antiquated technology lead to inefficient use of terminal area airspace. The efficacy of technologies to reduce separations and improve flight paths for high-density arrival and departure traffic flows, which may include aircraft with quite different performance characteristics, will be highly dependent on automation and precision positioning, navigation, and timing. R&D activities focused on a more thorough understanding of wake turbulence transport and decay can potentially allow for decreased separation standards and subsequent increased throughput for single and multiple runways. To accommodate increased arrival and departure rates, especially during low-visibility conditions, improvements in surface operations and situational awareness will be needed.

Research will lead to time-based metering of flows from metroplex areas (two or more adjacent airports where the arrival and departure operations are highly interdependent) into en-route traffic streams and to the integration of performance-based trajectory man-

agement tools and techniques for both arrival and departure flow in transitional airspace (defined as the portion of controlled airspace where aircraft change from one phase of flight or flight condition to another, for example, to/from the en-route to terminal environment). Since some noise abatement procedures constrain operations in this transitional airspace, technologies to enable approach and departure paths (including straight-in arrivals and straight-out departures) should be explored to enable improved noise and emission footprints. This research will allow for significant airspace design flexibility to exploit performance-based trajectories while taking into account constraints such as those due to different aircraft performance characteristics and to environmental restrictions.

Goal 5—Develop expanded aircraft capabilities to take advantage of increased air transportation system performance (see p. 42)

Realizing the maximum performance of the NAS requires an aircraft fleet designed in conjunction with the NAS itself. This goal focuses on developing knowledge, data, capabilities, technologies, and design tools for the classes of vehicles envisioned to be part of the commercial and general aviation fleets. These vehicles may have widely varying performance characteristics (e.g., rotorcraft or supersonic vehicles), with operational paradigms ranging from conventionally piloted vehicles to autonomous operations. This goal is also complementary to military aircraft and the goals described in both the national security and homeland defense and aviation safety sections. Further, this goal is based on the premise that to make revolutionary aircraft improvements possible, understanding the complete system (the aircraft and the air transportation system they fly in) is required. For this purpose, R&D is needed to credibly predict future improvements in NAS capacity that can be obtained while maintaining or improving safety standards and adhering to more restrictive environmental regulations.

Key advances in aircraft technologies, based on long-term, stable foundational research, are needed to bring about significant changes in the current fleet mix, such as advances in materials, physics-based flow prediction and control technologies, configurations, subsystems (including projected advances in machine intelligence), and components. For example, the fuel burn of future air vehicles must be decreased significantly, along with their noise and emissions (see Goals 2 and 3 included in the energy and environment section).

Additional access capabilities will be provided by future aircraft that are able to take off and land with significantly reduced field lengths. Economically viable aircraft capable of supersonic speeds over land (with an acceptable sonic boom impact) are also envisioned. Future rotorcraft concepts may also be developed to obtain a combination of vertical or short takeoff and landing capabilities and efficient cruise. Because of the highly integrated nature of the technologies that will be required to bring about these revolutionary improvements, the development of high-fidelity, physics-based, multidisciplinary analysis

and design capabilities is included in this goal, as is ensuring that validation and verification plans for these new capabilities are put in place.

Finally, this goal addresses the need to introduce new component technologies and vehicle concepts into the system in a timely fashion. Research in advanced manufacturing capabilities and changes in certification processes can decrease the cost and time for the introduction of new aircraft and aircraft subsystems without compromising safety. Research results are a critical source of information that inform the certification process. Timely, verified results from research studies are of particular importance in the development and allocation of requirements, standards, and criteria for certification of aircraft capabilities and operating procedures. Although final approval is the responsibility of the certification services, standards development requires the involvement of, and input from, the full stakeholder community, including governmental and nongovernmental entities.

AVIATION IS VITAL TO NATIONAL SECURITY AND HOMELAND DEFENSE

Aviation is a central part of America's National Security Strategy, providing needed capabilities to project military power around the globe in defense of U.S. interests and overcome a wide range of national security challenges. At the same time, the military must possess the ability, at a moment's notice, to seamlessly use the national airspace system for defense anywhere within and approaching U.S. borders.

INTRODUCTION

The United States faces a changing national security environment in which the Federal Government must address a broad range of challenges such as nontraditional, irregular warfare with non-state actors, weapons of mass destruction that could be used by either state or non-state actors, and disruptive technological advances by other states that could change the nature of warfare. The United States must also advance its technological advantage to retain air superiority in traditional peer-on-peer conflict. Growing aircraft acquisition costs and a need for shorter development cycles require that aeronautics R&D take a more strategic planning approach to mature new technologies and capabilities, while sustaining a robust technology base to support and advance U.S. military capabilities far into the future.

STATE OF THE ART

Aviation provides for many of the strategic and tactical needs of the warfighter, including strike; air superiority; command, control, intelligence, surveillance, and reconnaissance; and airlift. The military Services operate a variety of fixed- and rotary-wing aircraft in support of military operations. The Services continue to upgrade existing aircraft systems and acquire new systems with greater capability, though the rate of replacement is such that current air fleets are aging and many systems will be flying well beyond their original design lifetimes. The United States must continue to advance aviation technologies that provide increased capabilities to maintain its military effectiveness over potential adversaries. Moreover, today's uncertain security environment requires new approaches that increase battlespace awareness and flexibility to address a range of national security challenges. Aviation also provides a key component to disaster recovery and law enforcement activity, as well as humanitarian operations. Technology must address growing military acquisition and operating costs through advanced design and manufacturing capabilities, greater platform efficiency, and reduced maintenance costs and increased availability, while continuing to advance domestic capabilities for homeland defense operations.

FUNDAMENTAL TECHNICAL CHALLENGES TO OVERCOME

A number of fundamental challenges are barriers to technical progress, as well as opportunities for advancement through sustained aeronautics R&D:

- Improved aerodynamics and innovative airframe structural concepts for high-efficiency fixed- and rotary-wing aircraft would provide greater aircraft range, endurance, survivability, and payload capability.
- Quiet, efficient rotorcraft would be more operationally effective, more survivable, and less expensive to operate.
- Highly efficient propulsion systems would enable greater range and endurance and could provide greater mission flexibility.
- Integrated thermal and energy management on aircraft is becoming increasingly important as power requirements and heat loads increase.
- High-speed and hypersonic flight offers advantages for national security in terms of global reach, responsiveness, and survivability.
- Finally, airspace integration and deconfliction, especially as UAS become ubiquitous to aviation operations, are growing issues affecting not only military operations, but civil operations as well.

NATIONAL SECURITY AND HOMELAND DEFENSE R&D GOALS AND OBJECTIVES

National security and homeland defense aeronautics R&D plans are organized around capability-based planning concepts, but certain high-priority national goals are critical for enabling multiple capabilities. These goals represent a significant advance in the state of the art in terms of technology and current aviation capabilities, and they will continue to evolve as technology advances and in response to national security needs. In general, the Department of Defense seeks to develop technologies to a level where they can be validated or demonstrated in a relevant environment and ultimately be employed in weapon systems. However, there are areas of research where this guidance does not necessarily apply, such as with concept development or knowledge generation that is necessary to support a robust technology base. In addition to the objectives defined here, ongoing foundational aeronautics research efforts in areas such as: propulsion; aerodynamics; materials and structures; guidance, navigation, and control; acoustics; and mathematics and computational science focus on sustaining a robust technology base to continue to support and advance the nation's defense capabilities.

Goal 1—Demonstrate increased cruise lift-to-drag and innovative airframe structural concepts for highly efficient high-altitude flight and for mobility aircraft (see p. 43)

The ability to cruise efficiently at very high altitudes, enabled by a substantial increase in cruise lift-to-drag ratios over today's high-altitude reconnaissance aircraft, is a critical goal and key element in support of national security, providing sustained presence, long range, and advanced sensing capabilities. Specific technologies include: innovative configurations; large, lightweight, actively controlled wing structures; lightweight, high-strength, stiff materials; structurally integrated sensors; physics-based transition prediction; and

novel flow control techniques. Several of these technologies, as well as other structural concepts and aerodynamic configurations and technologies, are also applicable to mobility aircraft, that is, aircraft that provide airlift for national security and homeland defense materiel and personnel. For these applications, improvements in lift-to-drag ratios on the order of 25 percent compared to modern tube-and-wing aircraft would provide a significant advance in national security capabilities. Research efforts for mobility aircraft also leverage some of the work described in the energy and environment section for reducing aircraft fuel burn.

Goal 2—Develop improved lift, range, and mission capability for rotorcraft (see p. 43)

Future national security plans will benefit from rotorcraft systems that have: (1) significantly improved lift, range, survivability, and mission capability compared with year 2005 state-of-the-art technology; and (2) an overall reduction in logistics and cost of operation. The critical technologies to support these capabilities include the following:

- Advanced rotors and rotor hubs, possibly with active blade control, that produce higher lift with reduced noise and downwash.
- High-speed, high-torque drive trains that are quieter, more robust, and require less maintenance.
- Rotors, transmissions, and propulsion systems that allow large variations in rotor speed.
- Aircrew tools using knowledge-based information systems and management, sensors, displays, and controls optimized for combat and rescue mission effectiveness and survivability in day/night adverse weather operations.

Key advances in rotorcraft survivability also include more advanced threat warning and countermeasures and technologies to reduce rotorcraft acoustic signature.

Goal 3—Demonstrate reduced gas turbine specific fuel consumption (see p. 43)

A primary long-term goal in aircraft propulsion is to reduce system specific fuel consumption by more than 30 percent over gas turbine engines using year 2000 state-of-the-art technology. Such an advance in propulsion system performance would provide important improvements in aircraft range, endurance, mission flexibility, and payload capability. Technical challenges being pursued include: efficient, high-overall-pressure-ratio compression systems; variable-cycle engine technologies; advanced high-temperature materials and more effective turbine blade cooling; and techniques to more efficiently recuperate energy while satisfying thermal and power requirements. This area also leverages some of the work described in the energy and environment section for reducing aircraft fuel burn.

Goal 4—Demonstrate increased power generation and thermal management capacity for aircraft (see p. 43)

Additional sensor packages and advanced electronics, along with the potential development of airborne directed-energy weapons, require dramatic improvements in power and thermal management. At the same time, higher temperature propulsion systems and higher flight speeds will yield much higher heat loads to be managed by future aircraft, with some projections of heat loads reaching 10 times those of tactical military aircraft such as the F-15 or F-16. Key technologies to improve power generation and thermal management include: system-level modeling and simulation; compact integrated power and thermal management systems; high-temperature, high-pressure pumps and actuators; high-temperature heat exchangers; high-temperature fuel and oil systems; and advanced material solutions to support these subsystems.

Goal 5—Demonstrate sustained, controlled, hypersonic flight (see p. 43)

Several recent efforts have successfully demonstrated acceleration and cruise at hypersonic speeds, the flight regime beyond approximately Mach 5. These have included tests with airbreathing engines at speeds approaching Mach 10, albeit for very short durations. Successful sustained, controlled, hypersonic flight, which will be extremely challenging, requires continued R&D into all areas of high-speed atmospheric flight, including integrated aircraft design, aerodynamics, aerothermodynamics, structures and materials, lightweight and durable thermal-protection systems, supersonic combustion, and propulsion concepts that operate from subsonic speeds into the hypersonic regime.

Airspace integration and deconfliction for UAS

Another key challenge for national security and homeland defense is UAS airspace integration and deconfliction. Although a stand-alone goal in national security and homeland defense has not yet been established, it is clear that this challenge requires significant research in areas such as human-machine interaction, autonomous systems, and verification and validation. Research must also address integrating aircraft with different missions, different vehicle capabilities, and different command, control, and communication architectures. Efforts in this area leverage research described in the mobility and aviation safety sections on automation systems and integration of aircraft with different performance characteristics in the NAS.

AVIATION SAFETY IS PARAMOUNT

Every individual who enters an airport or boards an aircraft expects to be safe. To that end, continual improvement of flight safety must remain at the forefront of the U.S. aeronautics agenda.

INTRODUCTION

The current air transportation system—especially for commercial aviation—is extremely safe. The task before the United States is to maintain and improve this safety record as aviation traffic increases and new forms of aircraft create an increasingly complex aviation environment. As introduced in the mobility section, the potential increase in operations by a factor of 2–3 by 2025 implies an increased complexity in the monitoring and control of aircraft, as well as reduced time to react to problems. This requires new technologies, operating procedures, and methods for predicting and preventing safety issues if this increased complexity of aviation operations is to be achieved safely. If safety is addressed early in the design of fundamental transformations of the NAS, even greater levels of safety can be achieved.

Likewise, there is a need to understand the safety implications of a much broader variety of aircraft operating in the NAS that will be enabled by the NextGen. In the next 10 to 15 years, expanded general aviation, rotorcraft operations, UAS, and the nascent air taxi business all present tremendous opportunities to meet the demands of consumers, but they also provide new and unique safety concerns. Future generations of advanced aircraft that may enter into service in the 2020–2025 time frame, market permitting, will likely use revolutionary configurations such as hybrid wing-body, small supersonic jets, cruise-efficient short take-off and landing, or advanced rotorcraft, and may pose even more unique safety concerns. The operational characteristics of these aircraft, their safety envelopes, visibility to other aircraft, and responsiveness must be understood and considered when developing a safe air transportation system. The combined effect of increased complexity and diversity of aircraft creates major challenges to ensuring continued high levels of aviation safety while achieving the aviation capabilities needed for the nation's future.

STATE OF THE ART

The aviation industry provides by far the safest mode of transportation available in the United States. By the end of 2007, the average commercial fatal accident rate has declined to its lowest level—0.022 per 100,000 departures—a 57 percent drop over the last 10 years.[7] The decline in the accident rate highlights that safety is a core value throughout the entire aviation industry, across all classes of vehicles and the operation of the airspace system.

7 Federal Aviation Administration, "2008–2012 FAA Flight Plan: Charting the Path for the Next Generation," 2007, p. 15, http://www2.faa.gov/about/plans_reports/media/FPP_Flight%20Plan% 202008-2012.pdf.

The current system has reached a state where low accident levels for commercial aviation, coupled with the traditional forensic investigation approach to aviation safety, are yielding fewer insights capable of significantly improving aviation safety. Advances in prognostic techniques provide tools of choice for gaining insights into system safety through examination of large numbers of normal operations, as well as incident events.

Future aircraft will be made from advanced, novel materials, in more complex configurations, with more technically advanced subsystems and avionics. Increased numbers of aircraft in the air transportation system not only increase the aircraft density in the air, but also on the ground. Despite the excellent safety record for aviation today, accidents do occur. When they occur, it is imperative that the probability of survival for the passengers and crew onboard be as high as possible.

It is anticipated that automation will play a key role in future aircraft and the future NAS as enabled by NextGen. This issue will require advances in human-machine integration capabilities, better decision-making through data and knowledge mining systems, and control systems that adapt to unforeseen changes in the aircraft configuration and changing environmental conditions. In addition, improved software practices will be essential to the implementation of automation technologies. Software was identified as critical to aviation by both the President's Council of Advisors on Science and Technology ("the percentage of aircraft functionality enabled by software has grown from 10% in the 1960s to over 80% today"[8]) and the National Academy of Sciences ("Dependable software will be a linchpin of safe air transport in the coming decades"[9]). These automation systems will require extensive research in software verification and validation techniques to ensure their reliable performance.

FUNDAMENTAL SAFETY CHALLENGES TO OVERCOME

Shortfalls associated with the state of the art discussed above will have to be overcome to continually improve safety in the decades ahead. The following are the major challenges:

Monitoring and assessing the health of aircraft, at both the material and component level, more efficiently and effectively.

- Rapidly and safely incorporating technological advances in avionics into the aircraft.
- Applying novel sensing, control, and estimation techniques to assist in stabilizing and maneuvering next-generation aircraft in response to safety issues ranging from multiple-aircraft conflicts to on-board system failures in the NextGen airspace.

8 "Leadership Under Challenge: Information Technology R&D in a Competitive World." President's Council of Advisors on Science and Technology, August 2007.

9 "Software for Dependable Systems: Sufficient Evidence?" D. Jackson, M. Thomas, and L. I. Millett, Eds. National Research Council of the National Academies, May 2007.

- Understanding and predicting system-wide safety concerns of the airspace system and the vehicles as envisioned by NextGen, including the emergent effects of increased use of automation to enhance system efficiency and performance beyond current, human-based systems, through health monitoring of system-wide functions that are integrated across distributed ground, air, and space systems.
- Understanding the key parameters of human performance in aviation to support the human contribution to safety during air and ground operations for appropriate situational awareness and effective human-automation interaction, including off-nominal and degraded situations.
- Ensuring safe operations for the complex mix of vehicles anticipated within the airspace system enabled by NextGen.
- Enhancing the probability of passengers and crew to survive and escape safely when accidents do occur.

AVIATION SAFETY R&D GOALS AND OBJECTIVES

To continue today's impressive safety record while increasing the density of air traffic and the diversity of platforms will require foundational research and advanced system development in three focus areas: reliable and robust aircraft; safe air and ground operations; and accident survivability. Below are three goals and associated objectives to address the major challenges in continually improving safety in the NextGen.

Goal 1—Develop technologies to reduce accidents and incidents through enhanced vehicle design, structure, and subsystems (see p. 44)

Aircraft-level health-management systems, including sensors and analytical tools, will be developed that will identify problems before accidents occur. Research in health management requires not only monitoring and detecting, but also confident prognostics of latent potential failures before they occur. While health management is informed by the known accident and incident records of other vehicles, it is not restricted to those known conditions.

To reduce accidents caused by loss of stability and an aircraft's inability to maneuver, research will be performed that will facilitate implementation of advanced systems logic and architectures for aircraft control. Loss of stability and maneuverability can result from an upset condition due to adverse conditions such as actuator failures, structural damage, or stall-departure resulting from, for example, inadvertent encounters with hazardous weather conditions such as convective weather or icing.

Advanced health-management systems and advanced aircraft control techniques will require extensive research in the verification and validation of automation systems,

which will include research into the interaction of such automation systems with the human operators.[10]

Research will also be needed that will lead to the development of improved aircraft structures, physics-based prediction and control of fluid-structure interactions, materials, and designs in order to reduce material and structural failures due to operational use. Research to incorporate human operability, maintainability, and trainability early into the design process at both the subsystem and system level is also important.

Goal 2—Develop technologies to reduce accidents and incidents through enhanced aerospace vehicle operations on the ground and in the air (see p. 44)

Focused research on NextGen airspace system safety is directed at understanding the impact of operational concepts and organizational structures within the NextGen on safety, including establishing robustness to off-nominal conditions as a design goal. Methods and tools will be developed to analyze for emergent effects, such as system-wide safety issues that may arise even when all system components and human operators perform as expected. Likewise, understanding airport and airspace designs that can reduce the likelihood of incidents on the ground and in the air is important. These objectives will consider not only technological developments, but also the design of operating procedures and the impact of human performance.

Research will address the challenges introduced by greater density and diversity of flight operations. To allow more aircraft to operate in the limited airspace, aircraft users and developers will require: improved understanding of aircraft interaction dynamics; improved aircraft interfaces, including automation systems; and system adaptability to changing conditions. It is critical to develop improved human-machine interfaces while safely increasing flight deck[11] and ground controller automation. It is also critical to assess the software verification and validation of automation systems to the operation of vehicles in the airspace system.

An increased number of aircraft in the air transportation system not only increases the aircraft density in the air, but also on the ground. To address this increased demand, research is needed to develop systems that improve pilot and controller awareness of airport surface conditions (aircraft locations, ground vehicle locations, runway occupancy, and pavement conditions), particularly in low-visibility situations. While improving the situational awareness of flight crews and ground controllers is critical to reducing incidents and accidents on the ground, understanding changes to airport designs that can reduce the likelihood

10 Ibid.

11 These interfaces include not only the flight deck for crewed vehicles, but also the UAS operator for uncrewed vehicles, in order to support the research requirements discussed not only here, but in the mobility and national security and homeland defense sections as well.

of incidents on the ground is also important. Results of research under this goal will be directed at developing technologies for new ground capabilities to be integrated into aircraft, control towers, and runways.

Research into understanding the human-machine integration requirements of weather data[12] will be conducted for flight operations in the air, as well as for ground operations.

Accidents will also be reduced through research of system-wide, prognostic identification of safety risk, as well as instituting an integrated development safety assurance process. This research objective will organize and manage data from all users in the entire airspace system and mine those data to actively identify safety risks to the affected users, rigorously integrating both objective statistical techniques and operator reports of safety concerns.

In the NextGen system, many system functions, such as separation management, trajectory management and flow management, are contingent on the integrity and integration of data and information across many distributed air and ground systems. Moreover, those functions will be variable (e.g., variable separation standards) and based on the health and level of performance of the participating systems (e.g., the accuracy, integrity, and update rate of surveillance information from aircraft). Therefore, research is required to address the health of critical system functions and develop techniques for real-time monitoring and assessment.

Goal 3—Demonstrate enhanced passenger and crew survivability in the event of an accident (see p. 44)

Enhancing and protecting the safety of passengers, crews, and ground personnel in the event of an accident is the third research challenge to improving aviation safety. The research can be broken into two categories: (1) improving crash survivability of aircraft structures; and (2) improving evacuation and accident response procedures. At present, nearly half the aircraft fatalities in impact-survivable accidents are due to the effects of smoke and fire. Research into understanding and reducing flammability of aircraft interiors is essential to making impact accidents survivable for crews and passenger, as well as firefighters. Research into understanding the flammability of alternative fuels and smoke toxicity of advanced aircraft materials will be conducted.[13] Restraint systems integrated into and as strong as the supporting aircraft structure offer the possibility of providing increased occupant survivability; research into these systems is essential. Lastly, research on current and future evacuation and accident-response procedures will ensure that new aircraft entering the airspace system are as safe as—if not safer than—today's aircraft.

12 Weather data as described in mobility R&D goal 3, "Reduce the adverse impacts of weather on Air Traffic Management decisions."

13 Alternative fuels as described in the energy and environment section R&D goal 1, "Enable new aviation fuels derived from diverse and domestic resources to improve fuel supply security and price stability."

ASSURING ENERGY AVAILABILITY AND EFFICIENCY IS CENTRAL TO THE GROWTH OF THE AERONAUTICS ENTERPRISE, AND THE ENVIRONMENT MUST BE PROTECTED WHILE SUSTAINING GROWTH IN AIR TRANSPORTATION

Aviation must have reliable sources of energy and use that energy efficiently to enable aircraft and an air transportation system to meet growing demand in an economic fashion. Appropriate environmental protection measures must be part of strategies for continued growth in air transportation.

INTRODUCTION

Commercial and military aviation have transformed the United States and the world during the last 50 years, but there are concerns about the energy efficiency of the aviation enterprise and the future availability, supply security, and cost of aviation fuels. Effectively improving energy efficiency of the aviation enterprise would ease the demand for petroleum and reduce cost. It could also have a positive impact on the environment by reducing greenhouse gas emissions and local air quality impacts. Concerns about aviation's impact on the environment, which have accompanied its growth, could potentially restrict the ability of the aviation system to grow to meet national economic and mobility needs. Airport expansion or new construction is often a contentious issue because of noise, air quality, and water quality concerns. Although aviation only currently contributes 2–3 percent of anthropogenic greenhouse gases,[14] emissions from the sector are expected to grow in absolute terms, and concerns about the climate impacts of these emissions are also growing.

STATE OF THE ART

Nearly 100 percent of the fuel used in aviation operations today is derived from petroleum. The commercial supply of energy and its price stability are critical business concerns; fuel currently represents the largest operating cost for U.S. airlines. Every one-cent increase in fuel price translates into an additional $190 million in annual costs for the commercial aviation industry.[15] The efficiency of today's aircraft is on par with the primary choice in U.S. mass-market travel—the automobile. Today's commercial aircraft turbine engines are designed to optimize fuel efficiency, with overall engine efficiency around 30 percent for high-bypass turbofans.

Noise issues include takeoff, landing, taxi and engine run-up, aircraft flying over very quiet areas such as national parks, and sonic booms associated with supersonic flight. Aviation noise is primarily a quality-of-life issue for the public, although there are also associated health impacts. Noise remains a key environmental concern that undermines

14 Intergovernmental Panel on Climate Change Fourth Assessment Report, "Working Group 1: The Physical Science Basis," 2007.
15 Air Transport Association, http://www.airlines.org/economics/energy/.

efforts to increase airport capacity. Aircraft noise reduction has been historically driven by the introduction of new technologies. Further technology gains resulting in noise reduction will be challenging, but both the Quiet Aircraft Technology program, sponsored by NASA and the Federal Aviation Administration, and the Silent Aircraft Initiative, led by the Massachusetts Institute of Technology and Cambridge University, have laid the technological foundation for further gains. Research also continues for noise reduction on the next generation of single-aisle subsonic aircraft.

Emissions of nitrous oxides (NOx), carbon monoxide, unburned hydrocarbons (some of which are classified as hazardous air pollutants), and particulate matter are of concern in the vicinity of airports. Emissions of carbon dioxide (CO_2), water vapor, NOx, and particulate matter in the upper troposphere and stratosphere are also of concern because of their potential direct and indirect effects on Earth's climate. There is a good understanding regarding the fundamental physics and chemistry of the effect of aircraft-generated CO_2 on climate, but there are large uncertainties in our present understanding of the magnitude of climate impacts due to aviation NOx emissions, contrails and cirrus clouds. The impact of particulates and their role in enhancing cirrus cloudiness—and subsequently climate change—is not well understood.

FUNDAMENTAL ENERGY AND ENVIRONMENTAL CHALLENGES TO OVERCOME

Concerns about aviation's environmental impacts and energy efficiency may impede its ability to grow. Aviation must also have a reliable, diverse, and cost-effective energy supply. Key energy and environment challenges for aviation include the following:

- Development of alternative aviation fuels and energy is critical to enabling energy sources that are more diverse and environmentally friendly than those currently derived from petroleum.
- A more complete understanding of the complex interdependencies that exist between aircraft noise, emissions, and fuel burn is required for tackling these issues in a cost-beneficial manner.
- Improvement is required in the capability to optimize aircraft noise, fuel efficiency, and emissions impacts using advanced technologies, operational procedures, and computer models.
- Scientific uncertainties must be reduced to levels that enable appropriate action. Such uncertainties include: the overall life-cycle impacts of alternative aviation fuels; the impact from aviation emissions, such as NOx and particulate matter, on climate; and the impact of particulate matter and hazardous air pollutants on local air quality. Key process uncertainties to be overcome include approaches for quantifying aviation emissions and their global distribution. This quantification is also critical for assessing impacts to human health.

- Improvement in the modeling of pollutant concentrations around airports and throughout the atmosphere is needed. The scientific community is not currently able to reach consensus in quantifying the scale of, and the metrics associated with, aviation's impact on climate, including the relationships between long-term impacts like CO_2 and shorter lived impacts like NOx emissions, contrails and cirrus clouds.

ENERGY AND ENVIRONMENT R&D GOALS AND OBJECTIVES

The United States must lead in effectively tackling aviation's energy and environmental issues so that the flying public can continue to enjoy the benefits of mobility and so that aviation activities do not diminish the quality of life for residents living near airports, adversely affect human health, or contribute to longer term impacts such as climate change.

Meeting these goals and objectives will help lead to the following results:

- Energy security through supply diversity, geographically diverse refining and distribution processes, and enhanced energy efficiency of both the civil and military aviation enterprises.
- A reduction in absolute terms of the significant impacts on public health and welfare due to noise and air quality. In addition, a quantification of water quality impacts, and if necessary, their mitigation. Overall, the environmental footprint of aviation must continue to shrink, even while accounting for an anticipated two to three times growth in capacity of the U.S. system by 2025.
- A reduction in uncertainties about aviation emissions to allow sound and appropriate mitigating action to limit or reduce the impact of aviation greenhouse gas emissions.

Achieving these goals requires a significant advance in the state of the art in terms of technology and current aviation capabilities. Crucial to this advancement is the pursuit of long-term, stable foundational research, including atmospheric and combustion chemistry, fluid mechanics of internal flows, acoustics, and computational science. For purposes of the energy and environment R&D goals and objectives, "enable" means to advance the development of technologies or systems to levels that appropriately facilitate eventual industry uptake for commercial applications; fleet insertion will add to the time line of achieving environmental mitigation.

Goal 1—Enable new aviation fuels derived from diverse and domestic resources to improve fuel supply security and price stability (see p. 45)

Exploring the suitability of alternative sources of energy, particularly those produced from diverse resources, for aviation is essential to the aviation industry. Aviation requires energy-dense fuels now and into the foreseeable future. For economic security reasons, fuel needs to be produced from diverse resources. A clean-burning, renewable fuel that

contains few aromatic components and sulfur, operates at high temperature, and produces little particulate emissions is desired. The most reasonable near-term choice is the use of indigenously available feedstocks, such as natural gas, coal, oil shale, and petroleum coke, to produce drop-in replacements/supplements for petroleum-derived jet fuels. Renewable biofuels are currently not capable of supplying a large percentage of fuel needs, but higher yielding future feedstocks, such as algae or cellulosic biomass, may improve feedstock supply. The main advantage of using biofuels may be their potential to reduce overall life-cycle CO_2 impact. If the performance and cost issues can be overcome, biofuels are envisioned to be blended with synthetic or conventional jet fuels. Biomass offers the attraction of potentially lower net CO_2 emissions in the mid term. Other renewable fuels are attractive longer term options. Research will identify and assess potential environmental and performance costs and benefits of alternative fuels, with particular focus on limiting the environmental footprint of aviation.

In the near term, the research focus will be on evaluating the performance of alternative fuels in comparison with conventional fuels in associated systems; certification processes will also be considered. Evaluating the environmental impacts of the production of alternative fuels is also important.

In the mid term, the research will focus on enabling affordable "drop-in"[16] fuels that have large production potential, meet safety requirements, and are certifiable. Further, exploring renewable aviation fuels that reduce carbon footprints is key to limiting the growth in aerospace emissions. Mid-term research will also enable development of environmental best practices to help guide the production of alternative and conventional fuels.

In the far term, renewable, non-drop-in aviation fuels meeting the same criteria as those for drop-in fuels will be enabled. These renewable fuels may require some aircraft and engine changes, as well as new fuel supply systems and airport infrastructure for successful adoption.

Goal 2—Advance development of technologies and operations to enable significant increases in the energy efficiency of the aviation system (see p. 45)

In 2004, the U.S. commercial aviation industry moved 12 percent more people and 22 percent more freight than it did in 2000, while burning 5 percent less aircraft fuel.[17] Even so, fuel is one of the most significant costs to civil and military aviation. Fuel efficiency is not only good for the environment and energy security, it also makes business sense. Enabling new technologies, procedures, and improvements to aircraft and air traffic management to

16 A drop-in fuel is a fuel that can be used in existing aircraft and supporting infrastructure; drop-in fuel properties may vary from the average properties of conventional fuels within existing specification limits.

17 I. Waitz, J. Townsend, J. Cutcher-Gershenfeld, E. Greizter, and J. Kerrebrock, "Report to the U.S. Congress, Aviation and the Environment A National Vision Statement, Framework for Goals and Recommended Actions," December 2004.

reduce fuel burn of aviation is crucial. The approaches to reduce vehicle fuel consumption are to increase the vehicle cruise lift-to-drag ratio, decrease the empty weight fraction, and increase overall engine efficiency. Key to reducing drag is the ability to accurately represent and predict the airflow over the aircraft. This capability will be accomplished through the development of physics-based methods, validated by high-quality experimental or flight data. The new methods will enable developing technologies leading to a reduction in drag sources, such as turbulence and separation, and an increase in lift (with further reduced drag) by enhancing laminar flow. Active-control methods that prolong laminar flow, delay separation, or increase circulation will also be developed. Propulsive efficiency can be improved by advancing analytical methods to enable active flow control over fan blades, similar to that for the airframe. Other approaches such as enabling an ultra-high bypass engine will also be pursued. Advances in material and structures technology will reduce the overall structural weight of the airframe. These include inherently stronger, lighter weight materials as well as more efficient structural concepts. Research in airframe and propulsion efficiency also leverages the work described in the national security and homeland defense section for improving aircraft lift-to-drag ratios and for reducing propulsion system specific fuel consumption. In addition to subsonic flight efficiency, both airframe and propulsion efficiencies are needed to achieve the cruise efficiency required for supersonic flight. In the near term, new materials and advances in structural systems will enable a weight reduction of supersonic high-temperature airframe and propulsion systems, resulting in fuel efficiency. Advances in communication, navigation, and surveillance technology can be leveraged to optimize aircraft arrival and departure procedures, along with sequencing and timing on the surface, in the terminal area, and en route, thereby increasing airport and airspace throughput and reducing fuel burn.

Analytical tools to evaluate the elements associated with vehicle fuel consumption and fuel efficiency and to analyze the effect of technology solutions are critical to determining the value of various technology or operational approaches. In the near term, research will enable metrics and first-order empirical analytical capabilities to evaluate fuel efficiency enhancement strategies. In the mid term, the focus will be on maturing existing analytical tools that generally rely on empirical correlations and first-order approximations to include the introduction of additional elements, bringing the methods closer to a physics-based representation. The far-term objective will be the transition from the mid-term advanced empirical analytical tools to physics-based tools that rely on foundational principles. These analytical capabilities will require high-quality experimental or flight data for validation. Note that the specific objectives of Goal 2 are closely coupled with Goal 3, because decreasing fuel burn decreases the environmental impact of the aviation system.

Goal 3—Advance development of technologies and operational procedures to decrease the significant environmental impacts of the aviation system (see p. 45)

To ensure that technology and operational goals are appropriate, research on the environmental impacts of aviation is needed. It is necessary to focus on sufficiently reducing the uncertainties regarding the impacts of aviation on the environment so productive options can be explored to enable development of cost-beneficial solutions that minimize environmental impacts. Research should investigate the relationships among: aircraft emissions in the stratosphere, troposphere, and near the ground; contrail-induced cirrus cloud formation; ozone depletion associated with supersonic flight; climate response and subsequent impacts; and air quality. In the mid term, the focus is on furthering scientific understanding to enable understanding the interrelationships of various emissions (e.g., relative benefits of focusing on reducing NOx versus CO_2). Hence, in the mid term, mitigation strategies focus on limiting emissions while avoiding strategies that may worsen impacts. In the far term, enhanced scientific understanding will enable optimizing mitigation strategies to actually reduce the most serious impacts in the most cost-beneficial manner.

Another element of aviation's impact on the environment is noise. To address this issue, research will pursue overall reductions in noise and examine the trades between noise and emissions improvements. Efforts on source noise physics will bring together various prediction and calculation methods to characterize and reduce noise from subsonic and supersonic aircraft and rotorcraft. In addition, efforts to better understand the trades between noise and emissions on all types of aircraft (rotorcraft, subsonic, and supersonic) are aimed at: (1) enabling future generations of aircraft (N+1, N+2, and N+3) that permit better management of the energy resources and environmental impact; and (2) informing national and international regulatory processes for better decision making on noise, emissions, and sonic boom issues.

The interplay between noise and emissions must be better understood to inform regional or local regulatory requirements, including regulations regarding supersonic aircraft. The objective is to cost effectively limit or reduce potential environmental health and welfare impacts of aircraft noise and emissions, while eliminating uncertainties that could lead to misdirected or poorly targeted regulations. Enabling new technologies, procedures, and improvements to aircraft and air traffic management to reduce the noise and local and global emissions of the aviation sector is also crucial. Solutions that minimize the trade-offs between various environmental factors and result in simultaneous reductions in noise and local and global emissions are most attractive.

Finally, research efforts should consider complete life-cycle issues for aircraft to facilitate environmentally friendly manufacturing processes, reuse and recycling of materials, and development of quantitative tools for environmental cost-benefit assessments particular to aviation.

RESEARCH, DEVELOPMENT, TEST, AND EVALUATION (RDT&E) INFRASTRUCTURE PLAN

INTRODUCTION

The National Aeronautics R&D Policy calls for a national research, development, test and evaluation (RDT&E) infrastructure plan aligned with the national research priorities and objectives of the national aeronautics R&D plan. The Policy's guidelines also call for an infrastructure plan that will: (1) identify assets considered critical, from a national perspective; and (2) define an approach for constructing, maintaining, modifying, or terminating assets based on the needs of the broad user community. In addition, the Policy tasked the executive departments and agencies to develop cost and usage policies that facilitate interagency cooperation and utilization in the management of their respective RDT&E assets, as well as appropriate access by non-Federal users. Before the RDT&E infrastructure plan could be completed, the R&D challenges, goals and objectives (comprised in the national aeronautics R&D plan) needed to be developed with full consideration of inputs from the broad aeronautics community, including non-Federal stakeholders in industry and academia. Only then would it make sense to complete a RDT&E infrastructure plan aligned with those goals and objectives. This section provides an outline of the infrastructure plan that is to be completed.

SCOPE

The national aeronautics RDT&E infrastructure should support R&D by providing the capability and flexibility to test and evaluate a broad range of new aircraft and air transportation management systems, from component-level to full-scale, and to the extent practicable, to evaluate them at an enterprise level. Consistent with the Policy, the focus of the RDT&E infrastructure plan is on the experimental facilities and the computational resources in the overall infrastructure. In addition, the infrastructure includes the cyber-infrastructure that encompasses the hardware, software, and networking protocols that serve to tie together experimental facilities and computational resources. For the purposes of the infrastructure plan, aeronautics RDT&E infrastructure can be categorized by the following types of facilities: (1) high-end computational facilities, (2) simulation laboratories, (3) flight test facilities, and (4) ground test facilities.[18] It should be noted that the aeronautics RDT&E infrastructure must be supported by a skilled workforce, as well as RDT&E management processes. The workforce includes technicians, degreed specialists, and managers. Processes include distributed test and evaluation processes, interagency processes, and financial processes.

18 Note that departments and agencies have numerous aeronautics research laboratories that span a wide range of capabilities. Many are small, highly specialized, and focused on unique mission-specific activities and may not be appropriate for inclusion in a national infrastructure plan. Hence, their inclusion must be carefully considered and justified on a case-by-case basis.

The RDT&E infrastructure used by the nation's aeronautics community includes both domestic (i.e., national) and foreign assets. Note that both Federal and non-Federal assets, including assets from the private sector and academia, comprise the national infrastructure. The aeronautics R&D plan may also rely on certain foreign assets to meet the nation's requirements.

RDT&E INFRASTRUCTURE CHALLENGES TO OVERCOME

There are several challenges that the aeronautics RDT&E infrastructure must overcome to ensure its future success in supporting the aeronautics R&D goals and objectives and the needs of the broader aeronautics community.

- A national aeronautics RDT&E infrastructure will require a coordinated management structure that cuts across individual Federal agencies and provides a combination of assets to meet the needs of the aeronautics R&D plan—needs that reach beyond the traditional Federal agency stovepipes.
- The infrastructure plan must clearly identify the critical assets of the national RDT&E infrastructure to ensure that all necessary RDT&E capabilities are ultimately available to support the goals and objectives of the Plan. The infrastructure must be properly managed (e.g., maintained, modified, or terminated), based on national requirements.
- As technology advances into more sophisticated systems, the nation must develop increasingly more capable RDT&E infrastructure. For example, the plan needs to ensure that the United States builds a capability that serves the testing needs of the future enterprise to integrate physical hardware and simulations in a test environment utilizing a cyber-infrastructure that will play a prominent role in the future. Furthermore, RDT&E infrastructure plans for accommodating future testing needs for the aeronautics enterprise must recognize the challenge associated with confidently scaling the results of hardware/software/human-in-the-loop simulations to realize the complexity, diversity, and magnitude of the future operational system. It is possible that novel theory and analysis will be required to determine the appropriate means to scale such results to ensure that emergent large-scale system behaviors, in a system that has yet to be built, can be confidently predicted and accounted for. "Design of experiments" approaches for addressing areas such as human-automation interactions, particularly in off-nominal conditions, may need to be developed.
- The potential impacts on the national RDT&E infrastructure due to increased U.S. dependence on foreign infrastructure are not well understood. A review of the relationship between U.S. entities' practices with respect to foreign infrastructure and the effects of those practices will be necessary, as well as the identification of any potential impacts on the R&D plan's goals and objectives.

RDT&E INFRASTRUCTURE GOALS

Because a capable aeronautics test infrastructure is key to meeting the challenges, goals, and objectives of the nation's aeronautics R&D community, identification of the critical test capabilities and a plan for managing these assets is required. The infrastructure plan goals will address these issues and provide a basis for continued interagency and non-Federal stakeholder coordination on this crucial segment of the aeronautics enterprise.

Goal 1—Determine the national RDT&E infrastructure that satisfies national aeronautics R&D goals and objectives

The first goal is for the nation to have a RDT&E infrastructure that satisfactorily supports the national aeronautics R&D goals and objectives. Hence, the plan will call for an assessment of the necessary RDT&E infrastructure capabilities required to meet these goals and objectives. Those capabilities identified as necessary will be deemed critical. These findings will be followed by an assessment of the current aeronautics-related RDT&E infrastructure capabilities. Both of these findings will be organized around the broad types of facilities outlined above. In addition, the assessment of current RDT&E capabilities will include Federal, private sector, and foreign assets. A comparative analysis of these two assessments will lead to the identification of potential shortfalls in RDT&E capabilities, as well as potential redundancies. This work should be accomplished within a year of the establishment of an interagency working group that will be described further in the future implementation section.

While these steps are necessary to identify capabilities required to advance the nation's aeronautics R&D goals and objectives, they are not sufficient to meet the guidance of the Policy and ultimately determine which RDT&E assets should be constructed, maintained, modified, or terminated. It is clear that tradeoffs must be made between developing new capabilities and maintaining, modifying, or eliminating current ones. Modifying could include modernizing the infrastructure to incorporate continuing advances in computational resources for modeling and simulation, and associated data acquisition, processing, and control.

Providing recommendations on further actions for specific RDT&E assets will require an analysis of the broader test and evaluation and mission-specific needs of the departments and agencies, as well as the broader user community. Hence, the RDT&E infrastructure plan will call for further analysis—perhaps through coordination with broader organizational and managerial models to be explored in Goal 2 below—of these broader needs in order to make specific recommendations. This work will be started within the next year, but will take up to two to three years to complete before it can be useful so that the appropriate Federal departments and agencies can initiate planning, programming, and budgeting actions to sustain, improve, or terminate those assets.

Finally, the plan will address the need to develop a distributed cyber-infrastructure for the conduct of research and testing, in real time, in support of the goals and objectives of the aeronautics R&D plan. The integration of live testing with simulation increases the size and scale of the test environment, permitting testing to take place earlier in the system development process, increasing the efficiency, and reducing the cost of aeronautical testing. The initial scoping of the requirements for the cyber-infrastructure should be completed in a year. Further development of the requirements, as well as the processes, policies, methodologies, and protocols to operate the cyber-infrastructure should take up to two to three years to complete.

Goal 2—Establish a coordinated management approach for Federal RDT&E infrastructure that is based upon a national perspective and interagency cooperation

The second goal of the plan is to implement a management approach that facilitates close cooperation and reliance among various Federal agencies. The resulting management reforms must focus on an ultimate end-state where the national aeronautics RDT&E infrastructure supports users from government, as well as industry and academia. Coordinated management approaches must address key challenges to adequately maintain and upgrade critical facilities, terminate facilities that are no longer needed, construct new state-of-the-art ground and flight test capabilities as needed, and invest in advanced computational/simulation tools. Within applicable laws and regulations, the Federal agencies must develop cost and usage policies that facilitate interagency cooperation and utilization in the management of their respective RDT&E assets, as well as appropriate access for non-Federal users. To do that, the plan must overcome the tendency of owning/managing departments and agencies to focus their budgets and their management emphasis on their own needs rather than on national priorities. Consequently, it is imperative that the Federal agencies expand their interagency communication, cooperation, and reliance using arrangements similar to those that have proven successful in the recent past, such as the National Partnership for Aeronautical Testing (NPAT) Council and the National Coordination Office for Networking and Information Technology Research and Development.

For example, the Department of Defense (DOD) and NASA, through the NPAT Council, are jointly conducting facility assessments for each flight regime to analyze the technical capabilities of existing facilities and identify areas for greater access and use, as well as opportunities to terminate unnecessary or obsolete facilities. The first facility assessment being conducted focuses on test facilities supporting the transonic flight regime. This assessment, which will document the technical capabilities of the test facilities in the form of a technical report, will provide insights into the areas where DOD and NASA can better understand capability thresholds and further exploit a reliance relationship regarding use and access. This assessment will also provide information that the NPAT Council will review and consider for areas of cooperation and possible management efficiencies. The

infrastructure plan should call for a similar approach to facility assessments across the entire Federal aeronautical RDT&E infrastructure to identify the critical facilities necessary to support the near-, mid-, and long-term goals of the R&D plan.

As with the NPAT Council, the infrastructure plan will need to balance the Federal requirements with the needs of other contributors to the national infrastructure. Coordination with groups from industry, such as the U.S. Industry Test Facilities Working Group sponsored by the American Institute of Aeronautics and Astronautics, and similar groups from academia will ensure that the RDT&E infrastructure reflects national needs. Additionally, for the United States to advance in aeronautics technology, it must provide sufficient access to the RDT&E infrastructure for users that conduct aeronautical research.

Finally, the plan will call for a review of the processes and procedures regarding the use of foreign infrastructure by the U.S. Government and the effects of Federal investments in foreign infrastructure to ensure that such procedures align with the goals of the National Aeronautics R&D Policy. Concurrently, it will call for a review of the use of Federal infrastructure by foreign entities.

The availability of a fully capable, state-of-the-art infrastructure is critical to supporting the national aeronautics R&D goals and objectives. The nation must take the requisite steps to ensure that, through the development and implementation of a supporting RDT&E infrastructure plan, the critical infrastructure assets are available and operational in time to meet R&D goals and timelines. Although the RDT&E infrastructure is complex and expensive, the United States must make the commitment to responsibly manage, invest in, and secure its infrastructure to realize the national aeronautics R&D goals and objectives and advance U.S. technological leadership.

FUTURE IMPLEMENTATION

Consistent with Executive Order 13419, "National Aeronautics Research and Development," and the National Aeronautics Research and Development Policy, the Director of the Office of Science and Technology Policy will provide the following in support of this Plan:

- A supplemental report to this Plan with additional technical content on aeronautics R&D goals and objectives and a preliminary assessment of current relevant Federal aeronautics R&D activities to identify areas of opportunity for potential increased emphasis, as well as potential areas of unnecessary redundancy. This report will be completed within one year.
- A plan for aeronautics RDT&E infrastructure. In order to produce this Plan and serve as a coordinating mechanism to encourage implementation, the National Science and Technology (S&T) Council will establish a National Aeronautics RDT&E Infrastructure Interagency Working Group (IWG) under the Aeronautics S&T Subcommittee. The purpose of the IWG will be to fully develop and update the infrastructure plan and provide continuing oversight of its implementation. This IWG will be co-chaired by DOD, NASA and FAA representatives and will consist of four interagency Task Force Teams, consisting of Federal experts in aeronautical testing. These four Task Force Teams will focus on: (1) high-end computational facilities; (2) simulation laboratories; (3) flight test facilities; and (4) ground test facilities.
- The following actions will be accomplished by the RDT&E Infrastructure Interagency Working Group and the supporting Task Force Teams within one year from its establishment:
  - An assessment of the necessary RDT&E infrastructure capabilities required to meet the national aeronautics R&D goals and objectives. Those capabilities, organized around the broad types of facilities outlined above, that are identified as necessary will be deemed critical.
  - An assessment of the current aeronautics-related RDT&E infrastructure capabilities (including Federal, private sector, and foreign) organized around the broad types of facilities outlined above.
  - A comparative analysis of these two assessments that will lead to the identification of potential shortfalls in RDT&E capabilities, as well as potential redundancies.

- Working with other interagency bodies as appropriate, initiation of the development of a strategy to provide all necessary RDT&E capabilities and terminate those that are not necessary.
- Establishment of mechanisms to coordinate and engage with non-Federal stakeholders in the development of the RDT&E infrastructure plan.
- For each category of facility mentioned above, recommendations for an interagency cooperative management approach that will institutionalize the needed processes to accomplish the purposes of the RDT&E infrastructure plan as needed to enable the aeronautics R&D goals and objectives.

GOALS AND OBJECTIVES TABLES

NOTE on the following tables: Many of the technical goals displayed in the following tables were deliberately chosen to be technically challenging. Given that this Plan will be updated every two years with new information, some goals may be determined to be less achievable or more costly than originally thought or new goals may be developed that reflect new opportunities. Thus, the technical goals displayed in the following tables may be modified as more knowledge is gained.

Mobility R&D Goals and Objectives

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Goal 1 Develop reduced aircraft separation in trajectory- and performance-based operations (see pp. 13-14)	Develop separation standards that vary according to aircraft performance and crew training Develop nonradar 30-mile separation procedures for pair-wise maneuvers in oceanic airspace	Develop 5-mile nonradar separation procedures for current nonradar airspace Develop positioning, navigation and timing precision requirements for fixed- and variable-separation procedures	Demonstrate self-separation in at least one airspace domain Validate performance-based variable separation standards for multiple domains
	Develop Automatic Dependent Surveillance-Broadcast 3- to 5-mile spacing Develop positioning, navigation and timing (including backup) capabilities to support NextGen	Develop merging and spacing tools for continuous descent approaches Establish the basis for separation standards to increase the maximum number of aircraft per cubic mile of airspace	Implement human-machine interaction methods in a highly automated air transportation system
Goal 2 Develop increased NAS capacity by managing NAS resources and air traffic flow contingencies (see pp. 14-15)	Develop advanced airspace design concepts to support 3× operations Develop Special Use Airspace and general aviation access procedures to maximize capacity to match demand	Develop dynamically adjustable advanced airspace structures—including flow corridors—scalable to accommodate an interim target of an environment supporting 2× operations	Demonstrate dynamic allocation of NAS resources Develop automated flight and flow evaluation and resolution capabilities to support Air Navigation Service Provider negotiations
	Develop trajectory management methods for collaborative preflight routing including prediction, synthesis, and negotiation	Develop methodologies for the dynamic allocation of NAS resources	Demonstrate gate-to-gate trajectory-based flight planning and flow management
Goal 3 Reduce the adverse impacts of weather on air traffic management decisions (see p. 15)	Develop resolution and accuracy requirements for weather forecasting information Develop requirements for probabilistic weather prediction systems and methods for communicating forecast uncertainty	Develop technologies for sharing weather hazard information measured by on-board sensors with nearby aircraft Develop probabilistic weather forecast products that communicate uncertainty information	Integrate weather observation and forecast information in real time into a single authoritative source of current weather information Develop air traffic management decision strategies to reference a single authoritative weather source, including understanding impacts of disparate interpretations of the data
	Develop initial capability for net-centric four-dimensional weather information system, including enabling fusion of multiple weather forecast and observation products and researching the roles of human forecasters in applying operational expertise to augment automated, four-dimensional weather grids	Develop severity indices for aviation weather hazards to identify adverse weather impact	Reduce adverse impact of weather with NextGen Network-Enabled Weather
Goal 4 Maximize arrivals and departures at airports and in metroplex areas (see pp. 15-16)	Develop traffic spacing/management technologies to support high-throughput arrival and departure operations	Develop technologies and procedures for operations of closely spaced parallel runways	For an environment supporting 3× operations: Reduce lateral and longitudinal separations for arrival and departure operations Demonstrate technologies and procedures to support surface operations Develop time-based metering for flows transitioning into and out of high-density terminals and metroplex areas to enable significant airspace design flexibility
	Develop time-based metering of flows into high density metroplex areas	Develop performance-based trajectory management procedures for transitional airspace	
	Develop technology to display aircraft and ground vehicles in the cockpit to guide surface movement	Develop operations and procedures to integrate surface and terminal operations, especially in low-visibility conditions	

Mobility R&D Goals and Objectives—continued

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Goal 5 Develop expanded aircraft capabilities to take advantage of increased air transportation system performance (see pp. 16-17)	Develop validated multidisciplinary analysis and design capabilities with known uncertainty bounds for N+1 aircraft, and develop procedures for the interaction of a variety of vehicle classes with the airspace system (including N+1, very light jets, UAS, and other vehicle classes that may appear in the system)	Develop validated system analysis and design capabilities with known uncertainty bounds for N+2 and N+3 advanced aircraft, including their interaction with the airspace system	Develop suitable metrics to understand realizable trades between noise, emissions, and performance within the design space for N+2 and N+3 advanced aircraft
	Develop dynamic, need-based "fast-track" Federal approval process for airframe and avionics changes Develop aircraft capability priorities for NextGen through 2015 to support standards development and certification	Develop N+2 aircraft fleet and associated capabilities to support the development of procedures, policies, and methodologies for reduced cycle times to introduce aircraft and aircraft subsystem innovations	Continue development and refinement of procedures, policies, and methodologies supporting reduced cycle times for introduction of advanced (N+3 and beyond) aircraft and associated subsystem innovations
	Enable commercial supersonic aircraft cruise efficiency 15% greater than that of the final NASA High Speed Research (HSR) program baseline	Enable advanced technologies for N+2 aircraft with significantly improved performance and environmental impact Enable commercial supersonic aircraft cruise efficiency 25% greater than that of the final NASA HSR program baseline Enable the development of N+2 cruise-efficient short takeoff and landing aircraft, including advanced rotorcraft, with between 33% and 50% field length reduction compared with a B737 with CFM56 engines*	Enable advanced technologies for N+2 and N+3 aircraft with significantly improved performance and environmental impact Enable N+2 and N+3 commercial supersonic aircraft cruise efficiency 35% greater than that of the final NASA HSR program baseline (through reductions in structural and propulsion system weight, improved fuel efficiency, and improved aerodynamics and airframe/propulsion integration)

* The reference aircraft is a B737-800 with CFM56/7B engines, representative of 1998 entry into service technology.

National Security and Homeland Defense R&D Goals and Objectives

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Goal 1 Demonstrate increased cruise lift-to-drag and innovative airframe structural concepts for highly efficient high-altitude flight and for mobility aircraft (see pp. 19–20)	Develop design methods for efficient, flexible, and lightweight aerostructures Demonstrate conformal load-bearing antenna elements and shape sensing subsystems	Demonstrate 20% delay in laminar to turbulent transition over a 30° swept laminar flow airfoil Demonstrate key component technologies for novel configurations with a substantial improvement in lift-to-drag ratios for uncrewed intelligence, surveillance, and reconnaissance applications	Flight demonstrate novel aerodynamic configurations with a substantial improvement in lift-to-drag ratios for uncrewed intelligence, surveillance, and reconnaissance applications
	Develop novel planforms and concepts for mobility aircraft through advanced aerodynamic and structural analysis	Demonstrate key component technologies for novel configurations with >25% improvement in lift-to-drag ratios for mobility aircraft	Demonstrate novel configurations with >25% improvement in lift-to-drag ratios for mobility aircraft
Goal 2 Develop improved lift, range, and mission capability for rotorcraft (see p. 20)	Increase power to weight (+40%) and reduce noise of main rotor gearbox (–15 dB)	Increase power to weight (+55%) and reduce noise of main rotor gearbox (–18 dB)	
		Reduce vibratory loads 25%; improve forward flight efficiency 5%	Reduce vibratory loads by 30% and improve forward flight efficiency by 10%
	Develop integrated threat warning and countermeasures	Test integrated threat warning systems	
	Develop analytical tools and component technologies for advanced low-noise rotor concepts	Flight test tactically significant acoustic-signature reduction	Demonstrate 50% reduction in acoustic perception range
Goal 3 Demonstrate reduced gas turbine specific fuel consumption (see p. 20)	Design and demonstrate high-pressure compressor technologies for high-overall-pressure-ratio propulsion systems through key component tests	Demonstrate a high-overall-pressure-ratio propulsion system enabling a 25% or greater specific fuel consumption reduction	Develop and demonstrate advanced propulsion concepts with variable-cycle features and high-overall-pressure ratio enabling a greater than 30% specific fuel consumption reduction
	Design and demonstrate variable-cycle propulsion component technologies through key component tests	Demonstrate a variable-cycle propulsion system enabling a 25% or greater specific fuel consumption reduction	
Goal 4 Demonstrate increased power generation and thermal management capacity for aircraft (see p. 21)	Demonstrate 2× operating temperatures for power electronics	Demonstrate 5× increase in thermal transport and heat flux for power electronics	Demonstrate 10× increase in thermal transport and heat flux for directed-energy weapons
	Demonstrate 4× increase in generator power density for directed-energy weapons	Demonstrate high-efficiency fuel pump with 65% reduced heat	Demonstrate 50% weight and volume reduction for aircraft power and thermal management systems
	Demonstrate >60 W/kg power density for UAS rechargeable energy storage	Demonstrate 2× power density for UAS hybrid energy storage	
Goal 5 Demonstrate sustained, controlled, hypersonic flight (see p. 21)	Demonstrate sustained, controlled flight at Mach 5–7 using hydrocarbon fuel	Ground test scramjet propulsion systems to 10× airflow of today's scramjet technology Increase thermal balance point to Mach 8+ on hydrocarbon fuel	Demonstrate scramjets operable to Mach 10 on hydrocarbon fuel and to Mach 14 on hydrogen fuel
	Ground test hypersonic vehicle component technologies, including high-temperature structures, thermal protection systems, adaptive guidance and control, and health-management technologies	Flight test air-breathing vehicle technologies beyond Mach 7 for application to space launch systems and possible reconnaissance/strike systems	Demonstrate a lightweight, durable airframe capable of global reach

Aviation Safety R&D Goals and Objectives

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Goal 1 Develop technologies to reduce accidents and incidents through enhanced vehicle design, structure, and subsystems (see pp. 24–25)	Develop vehicle health-management systems to determine the state of degradation for aircraft subsystems	Develop and demonstrate tools and techniques to mitigate in-flight damage, degradation, and failures	Develop reconfigurable health-management systems for managing suspect regions in N+2 vehicles
	Develop and test adaptive-control techniques in flight to enable safe flight by stabilizing and establishing maneuverability of an aircraft from an upset condition	Develop, assess, and validate upset recovery from vehicle damage using adaptive control augmenting strategies	Develop formal methods to verify and validate the safety performance margins associated with adaptive control augmenting strategies, decision making under uncertainty, and flight path planning and prediction
	Develop improved mitigation techniques that prevent, contain, or manage degradation associated with aging, and show that tools and methods can predict the performance improvement of these techniques	Deliver validated tools and methods that will enable a designer or operator to extend the life of structures made of advanced materials	Develop advanced life-extension concepts (designer materials and structural concepts) by using physics-based computational tools
Goal 2 Develop technologies to reduce accidents and incidents through enhanced aerospace vehicle operations on the ground and in the air (see pp. 25-26)	Validate and verify methods that enable improvements in pilot and controller workload, awareness, and error prevention and recovery, including during off-nominal scenarios, given the increased automation assumed in NextGen	Develop human-machine interfaces that enable effective human monitoring during highly dynamic conditions and allow for flexible intervention to ensure safety	Develop formal methods to verify and validate adaptive automation systems that support error prevention and recovery during off-nominal events in NextGen
	Develop flight deck displays and automation to convey up-to-date weather conditions and near-term forecasts Investigate in-situ and remote observing systems, technologies, and architectures that will provide hazardous and other weather information	Develop an integrated flight deck system that alerts flight crews of hazardous weather ahead and defines and coordinates a flight path that avoids the hazard Develop in-situ and remote observing technologies, systems, and architectures that will provide weather information to flight crews and meet air traffic management needs	Develop high-confidence, flight deck decision-support tools that use single authoritative weather information source for shared decision-making between air traffic management and flight crew
	Develop advanced tools that translate numeric (continuous and discrete) system performance data into usable, meaningful information for prognostic identification of safety risks for system operators and designers Understand the concepts of degradation and failure as well as other potential safety issues associated with critical system functions integrated across highly distributed ground, air, and space systems	Develop advanced methods to automatically analyze textual safety reports and extract system performance information for prognostic identification of safety risks for system operators and designers Develop techniques to enable real-time monitoring and assessment of critical system functions across distributed air and ground systems	Develop fundamentally new data-mining algorithms to support automated data analysis tools to integrate information from a diverse array of data resources (numeric and textual) to enable rapid prognostic identification of system-wide safety risks Validate and verify automation that safely and gracefully degrades critical system functions based on real-time monitoring and assessment
Goal 3 Demonstrate enhanced passenger and crew survivability in the event of an accident (see p. 26)	Develop occupant-restraint design tools that support occupant crash protection that is as strong as the fixed- and rotary-wing aircraft structure	Validate integrated vehicle structure and occupant restraint tools	Validate integrated vehicle structure and occupant restraint tools for advanced concept vehicles
	Develop analytical methodologies to model dynamic events in aircraft crashes to enable the development of lightweight and crash-absorbing airframe technologies for the fixed- and rotary-wing legacy fleet	Establish analytical methodologies to model dynamic events in aircraft crashes to enable the development of lightweight and crash-absorbing airframe technologies for advanced aircraft, including those made with advanced composite and metallic materials	Validate and verify analytical methods that model dynamic events in aircraft crashes for airframe structures
	Assess and reduce flammability and smoke toxicity of advanced materials to be used in aircraft platforms	Determine fuel vapor characteristics of alternative aviation fuel spills for post-crash survivability	Determine evacuation procedures as needed based on vapor characterization of fuel spills with alternative aviation fuels for post-crash survivability

Energy and Environment R&D Goals and Objectives

(Refer to notes on the next page)

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Goal 1 Enable new aviation fuels derived from diverse and domestic resources to improve fuel supply security and price stability (see pp. 29–30)	Evaluate performance of alternative versus conventional fuels in associated systems, including consideration of certification processes	Enable affordable "drop in"[a] fuels that have large production potential, meet safety requirements, and are certifiable Explore renewable aviation fuels that reduce carbon footprints	Enable renewable aviation fuels that meet safety requirements, are certifiable, have a large production potential, and are sustainable for aircraft and support systems
	Evaluate alternative fuel-production impacts on the environment	Enable environmental best practices in alternative and conventional fuel production	Enable new aircraft, fuel supply systems, and airport infrastructure to adopt alternative fuels that are not considered "drop in"
Goal 2 Advance development of technologies and operations to enable significant increases in the energy efficiency of the aviation system (see pp. 30–31)	Define achievable energy efficiency gains via operational procedure improvements Research operational procedures to enhance fuel efficiency Enable fuel efficient N+1 aircraft and engines (33% reduction in fuel burn compared to a B737/CFM56[g])	Research and enable new energy efficient operational procedures optimized for energy intensity (3–5% energy intensity improvement[b] for the energy efficient procedures over existing 2006 baseline procedures) Enable fuel efficient N+2 aircraft and engines (at least 40% reduction in fuel burn compared to a B737/CFM56[g]) Enable field length improvements for N+2 cruise efficient short takeoff and landing aircraft, including advanced rotorcraft (for details refer to Goal 5, mobility section)	Enable new energy efficient operational procedures optimized for energy intensity (6–10% energy intensity improvement for the energy efficient procedures over existing 2006 baseline procedures) Enable fuel efficient N+3 aircraft and engines to reduce fuel burn by up to 70% compared with a B737/CFM56[g] (70% is a 25-year stretch goal and assumes significant advances in novel configurations, engine performance, propulsion/airframe integration, and materials) Enable N+2 and N+3 commercial supersonic aircraft cruise efficiency 35% greater than that of the final NASA High Speed Research (HSR) program baseline (for details refer to Goal 5, Mobility section)
	Enable metrics and first-order empirical analytical capabilities to evaluate fuel efficiency enhancement strategies	Develop advanced empirical analytical capability to assess and enhance fuel efficiency enhancement strategies	Enable physics-based simulation analytical capability to optimize fuel efficiency enhancement strategies
Goal 3 Advance development of technologies and operational procedures to decrease the significant environmental impacts of the aviation system (see p. 32)	Research and develop ground, terminal, and en-route procedures to reduce noise and emissions and determine sources of significant impact	Develop and demonstrate advanced ground, terminal, and en-route procedures to reduce significant noise and emissions impacts	Develop new approaches and models for optimizing ground and air operational procedures
	Develop improved tools and metrics to quantify and characterize aviation's environmental impact, uncertainties, and the trade-offs and interdependencies among various impacts Enable quieter and cleaner N+1 aircraft and engines (32 dB cumulative below Stage 4);[c] LTO[d] NOx emissions reduction (70% below CAEP[e] 2 standard) Continue research to identify alternatives to lead as an octane-enhancing additive in aviation gasoline	Reduce uncertainties in understanding aviation climate impacts to levels that enable limiting significant impacts Characterize PM2.5[f] and hazardous air pollutant emissions and establish long-term goals for reducing to appropriate levels Enable N+2 aircraft and engines; (42 dB cumulative below Stage 4); LTO NOx emissions reduction (80% below CAEP 2) Enable a 70% reduction in high-altitude emissions for supersonic aircraft (reference HSR configuration)	Continue to reduce uncertainties in understanding aviation climate change impacts to levels that enable reducing significant impacts Enable physics-based analytical capabilities to characterize environmental impacts of aviation noise and emissions Enable N+3 aircraft and engines to decrease the environmental impact of aircraft (62 dB cumulative below Stage 4 (a 25-year goal); LTO NOx Emissions reduction better than 80% below CAEP 2) Enable an order-of-magnitude reduction in high-altitude emissions for supersonic aircraft (reference HSR configuration)
	Determine significant water quality impacts of increased aircraft operations	Enable anti-icing and deicing fluids and handling procedures to reduce water quality impacts determined to be significant	Enable environmentally improved aircraft materials and handling of fuel and de-icing fluids
	Develop predictive capabilities for rotorcraft noise	Enable low-noise acoustic concepts for low-noise rotary-wing vehicles	Enable low-noise operation and high-speed, fuel efficient rotorcraft
		Enable ~15 EPNdB[i] of jet noise reduction relative to unsuppressed jet for supersonic aircraft	Enable ~20 EPNdB of jet noise reduction relative to unsuppressed supersonic aircraft exhaust
	Enable reducing loudness ~25 PLdB[h] relative to military aircraft sonic booms	Enable reducing loudness ~30 PLdB relative to military aircraft sonic booms	Enable reduction of loudness ~35 PLdB relative to military aircraft sonic booms

Notes for the Energy and Environment R&D Goals and Objectives Table

a A "drop in" fuel is a fuel that can be used in existing aircraft and supporting infrastructure; drop in fuel properties may vary from average properties of conventional fuels within existing specification limits.

b Energy intensity is the ratio of energy consumption to economic or physical output. Potential metrics for aviation could be fuel consumption per distance, per passenger distance, or per payload.

c Current noise standard for subsonic jet airplanes and subsonic transport category large airplanes, *http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgFinalRule.nsf*.

d LTO is the landing and takeoff cycle.

e CAEP is the International Civil Aviation Organization Committee on Aviation Environmental Protection.

f Particles less than 2.5 μm in diameter.

g The reference aircraft is a B737-800 with CFM56/7B engines, representative of 1998 entry into service technology.

h PLdB = Perceived Loudness in decibels

i EPNdB = Effective Perceived Noise (level) in decibels

Plan prepared by

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL (NSTC)
COMMITTEE ON TECHNOLOGY (COT)
AERONAUTICS SCIENCE and TECHNOLOGY (AS&T) SUBCOMMITTEE

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The Honorable C.H. Albright Jr., Department of Energy

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Dr. Kohl S. Gill

Department of Homeland Security
Randel L. Zeller
Michael B. Smith

Department of Transportation
Dr. Richard R. John
Laurence T. Phillips

Joint Planning and Development Office
Robert A. Pearce
Dr. Edgar G. Waggoner

Federal Aviation Administration
Dr. Catherine A. Bigelow
Patrick L. Lewis
Barry C. Scott

National Aeronautics and Space Administration
Dr. Jaiwon Shin
Manfai Fong

National Science Foundation
Dr. Michael M. Reischman

Office of Management and Budget
Dr. Joydip Kundu

National Security Council
Peter J. Marquez

Office of the Vice President
Richard Heimerle

Domestic Policy Council
Christopher C. Papagianis

Council of Economic Advisors
Dr. Erik W. Durbin

Office of the U.S. Trade Representative
Willis Martyn
Kenneth Schagrin

U.S. International Trade Commission
Peder A. Andersen

Department of State
Dr. Robert Rudnitsky

Coordinating Group Members Supporting the AS&T Subcommittee

MOBILITY COORDINATING GROUP

Dr. Karlin R. Toner
National Aeronautics and Space Administration (Co-Lead)

Dr. Edgar G. Waggoner
Joint Planning and Development Office (Co-Lead)

Guy St. Sauveur
Department of Defense

Dr. Karsten Shein
Department of Commerce

Kevin L. Johnston
Department of Commerce

Dr. Lynn A. Sherretz
Department of Commerce

Dr. Richard R. John
Department of Transportation

Dr. Stephen G. Nash
National Science Foundation

Stanley G. Benjamin
Department of Commerce

Steven D. Lang
Federal Aviation Administration

Dr. Thomas P. Russell
Department of Defense

NATIONAL SECURITY AND HOMELAND DEFENSE COORDINATING GROUP

Dr. James A. Kenyon
Department of Defense (Lead)

Douglas Bowers
Department of Defense

Dr. William Borger
Department of Defense

Dr. Katherine Stevens
Department of Defense

Dr. Suzy Young
Department of Defense

Dr. Juan J. Alonso
National Aeronautics and Space Administration

Brian Hager
Department of Defense

William Koop
Department of Defense

Dr. Richard Fingers
Department of Defense

Dr. Keith Number
Department of Defense

Parker Buckley
Department of Defense

Joseph Harrington
Department of Defense

Gregory Fronista
Department of Defense

Malinda Pagett
Department of Defense

Peter Maloney
Department of Defense

Ming-Leung Lau
Department of Defense

David Masters
Department of Homeland Security

Richard Jehlen
Federal Aviation Administration

Richard Dennis
Department of Energy

Rori Marston
National Oceanic and Atmospheric Administration

SAFETY COORDINATING GROUP

Herbert W. Schlickenmaier
National Aeronautics and Space Administration (Co-Lead)

Dr. Catherine A. Bigelow
Federal Aviation Administration (Co-Lead)

John Seibert
Department of Defense

Ken Christensen
Department of Homeland Security

Robert A. Pappas
Federal Aviation Administration

Patrick L. Lewis
Federal Aviation Administration

ENERGY AND ENVIRONMENT COORDINATING GROUP

Dr. Lourdes Q. Maurice
Federal Aviation Administration (Co-Lead)

David L. Richards
Department of Defense (Co-Lead)

Dr. Kulvinder S. Gill
Department of Energy (Co-Lead)

Dr. James A. Kenyon
Department of Defense

Dr. Robert Rudnitsky
Department of State

Robert D. Brenner
Environmental Protection Agency

Sabrina R. Johnson
Environmental Protection Agency

Curtis A. Holsclaw
Federal Aviation Administration

Vicki K. Crisp
National Aeronautics and Space Administration

David Fahey
National Oceanic and Atmospheric Adminstration

A.R. Ravishankara
National Oceanic and Atmospheric Administration

Dr. Cindy M. Lee
National Science Foundation

Aimee F. Fisher
Federal Aviation Administration

RDT&E INFRASTRUCTURE COORDINATING GROUP

Blair B. Gloss
National Aeronautics and Space Administration (Co-Lead)

Phyllis L. Ferguson
Department of Defense (Co-Lead)

Dr. Richard R. John
Department of Transportation

Robert A. Pappas
Federal Aviation Administration

Gwynn A. Severt
National Aeronautics and Space Administration

Catherine H. Schulbach
National Aeronautics and Space Administration

Brian Barr
National Aeronautics and Space Administration

Mark Amundson
Department of Defense

John Thomas Best
Department of Defense

Dr. Andrew Mark
Department of Defense

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Aeronautics Science and Technology Subcommittee
National Science and Technology Council