TECHNICAL APPENDIX

National Plan for Aeronautics Research and Development and Related Infrastructure

EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

December 2008

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

December 17, 2008

Dear Colleague:

This Technical Appendix to the National Plan for Aeronautics Research and Development and Related Infrastructure (Plan) is the third in a series of National Science and Technology Council (NSTC) documents directed at providing a national policy and planning foundation for aeronautics research and development (R&D).

The series began with the National Aeronautics Research and Development Policy (Policy) that was enacted by Executive Order (EO) 13419 – National Aeronautics Research and Development in December, 2006. As part of the implementation of the Policy, EO 13419 called for a plan for national aeronautics R&D and related infrastructure. The National Plan for Aeronautics Research and Development and Related Infrastructure (Plan) was developed and subsequently approved in December 2007. This Technical Appendix fulfills a requirement in the Plan to provide a supplemental report with additional technical content on the aeronautics R&D goals and objectives as well as 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 Technical Appendix will also be useful in supporting the biennial update process for the Plan as required by EO 13419, thereby improving the coordination of national aeronautics R&D policy and planning guidance for the conduct of U.S. aeronautics R&D activities through 2020. By coordinating a common planning focus for the departments and agencies to define and achieve high priority national aeronautics R&D goals and objectives, we will help ensure that our Nation advances its 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 Marburger

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

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National Plan for Aeronautics Research and Development and Related Infrastructure

December 2008

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

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EXECUTIVE SUMMARY

On December 20, 2006, Executive Order (EO) 13419 – National Aeronautics Research and Development – established the National Aeronautics Research and Development Policy (Policy) to help guide the conduct of U.S. aeronautics research and development (R&D) programs through 2020. As part of the implementation of the Policy, EO 13419 called for a plan for national aeronautics R&D and related infrastructure.

The National Plan for Aeronautics R&D and Related Infrastructure (Plan) was approved in December 2007 and was organized according to the Principles contained in the National Aeronautics R&D Policy. The Plan established aeronautics R&D challenges, prioritized goals, time-phased objectives, and called for the development of a supplemental report with additional technical content in support of the Plan.

This Technical Appendix fulfills the requirements in the Plan for a supplemental report with: (1) additional technical content on the aeronautics R&D goals and objectives, and (2) a preliminary assessment of current relevant federal aeronautics R&D activities to identify areas of opportunity for potential increased emphasis and unnecessary redundancies. In conducting the preliminary assessment of current relevant federal aeronautics R&D activities and analyzing how well these activities meet the national aeronautics R&D goals, a methodology was developed that considered four key issues for each goal:

- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the near term;
- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the mid to far term;
- The level of coordination among executive departments and agencies (D&A); and
- The level of redundancy of efforts among executive departments and agencies.

Each of these four areas was given a broad assessment of green, yellow, or red based on this review. A green assessment denotes that R&D activities planned or ongoing are sufficient to achieve the objectives in the time frame indicated, that there is strong coordination among executive departments and agencies, and that there is no unnecessary redundancy. A yellow assessment indicates that R&D activities should provide significant progress toward the objectives but there is some risk due to fiscal or other constraints that merits continued attention, that coordination is taking place but could be improved, or that there does not appear to be unnecessary redundancy but additional coordination may be warranted. A red assessment highlights an area where additional emphasis or improved coordination among executive departments and agencies may be warranted to achieve the objective.

The results from this preliminary assessment indicate that, in general, aeronautics R&D for the Federal Government is adequate with most of the activities rated as either green (i.e., sufficient to achieve the objectives, good interagency coordination, or no unnecessary redundancy) or yellow (i.e., sufficient to achieve the objectives with some risk, or interagency coordination is occurring but could be improved). A few areas, however, were assessed to be in need of increased emphasis and/or coordination if the objectives are to be realized. These areas are summarized below (organized according to their respective Principles[1]):

- *Mobility through the air is vital to economic stability, growth, and security as a Nation*—No areas were identified.
- *Aviation is vital to national security and homeland defense*—Opportunities exist to improve the mid- and far-term rotorcraft R&D related to improving power-to-weight ratios, forward flight efficiency, and to reduce noise and vibratory loads. Additionally, there are mid- and far-term opportunities to significantly reduce gas turbine engine specific fuel consumption and to flight test air-breathing hypersonic vehicles with global reach.
- *Aviation safety is paramount*—Opportunities exist in the mid and far terms to enhance the ability to validate integrated vehicle structure and occupant restraint tools for future vehicles.
- *Assuring energy availability and efficiency*[2] *is central to the growth of the aeronautics enterprise, and the environment must be protected while sustaining growth in air transportation*—Opportunities exist in the near, mid, and far terms to enable the certification and future use of alternative fuels for civil aviation, increase subsonic civil aircraft fuel efficiency, and understand the impacts of and reduce subsonic fixed-wing aircraft noise and engine emissions.

In all these areas, no unnecessary redundancy was found.

Areas of opportunity for potential increased emphasis that have been identified are now able to be assessed by the appropriate executive departments and agencies, as well as by the larger aeronautics community through ongoing outreach by the Aeronautics Science and Technology Subcommittee of the Committee on Technology to the National Science and Technology Council. Further, it is envisioned that these identified areas will be considered in future biennial updates to the Plan as are required by EO 13419.

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[1] Two additional Principles were not addressed in the Plan: (1) Aviation Security R&D efforts are coordinated through the National Strategy for Aviation Security and its supporting plans, and (2) Aerospace Workforce issues are being explored by the Aerospace Revitalization Task Force led by the Department of Labor pursuant to Public Law 109-420.

[2] Energy and Environment were separate Principles in the Policy; however, they are sufficiently integrated that they were considered together in the Plan.

This Technical Appendix will also be used as a key input into the development of the National Aeronautics RDT&E Infrastructure Plan, also called for by the National Plan for Aeronautics R&D and Related Infrastructure. This Infrastructure Plan will primarily focus on the capabilities and policies of the Federal Government for the aeronautics RDT&E facilities it owns or manages.

INTRODUCTION

On December 20, 2006, Executive Order (EO) 13419, "National Aeronautics Research and Development," established the nation's first policy to guide Federal aeronautics research and development (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 R&D and for related infrastructure that would be updated biennially.[3]

The National Aeronautics R&D Policy (Policy) established by EO 13419 laid out seven key Principles to guide the conduct of the nation's aeronautics R&D activities through 2020:

- 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.[4]
- The United States should continue to possess, rely on, and develop its world-class aeronautics workforce.[5]
- 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.[6]

These Principles, with the two exceptions noted, served as the framework for the National Plan for Aeronautics Research and Development and related Infrastructure (Plan) that was approved by the President in December 2007. For each Principle addressed, the Plan included a description of the state of the art of related technologies and systems and a set of fundamental challenges and associated high-priority R&D goals that seek to address these challenges. To give additional clarity and definition, the Plan provided supporting objectives for each goal. These objectives were phased over three time periods: near term (<5 years), mid term (5–10 years), and far term (>10 years).

As part of implementation actions, the Plan called for the development of a supplemental report with additional technical content on the aeronautics R&D goals and objectives. This Technical Appendix fulfills the requirement for the supplemental report and contains further explanation of the R&D challenges as well as a description of current R&D activities

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[3] http://www.ostp.gov/aeroplans/pdf/aerordEO12_20_06final.pdf.

[4] Aviation security R&D efforts are coordinated through the National Strategy for Aviation Security and its supporting plans, hence were not covered in the Plan.

[5] Aerospace workforce issues are being explored by the Aerospace Revitalization Task Force led by the Department of Labor pursuant to Public Law 109-420, hence were not covered in the Plan.

[6] Energy and Environment were separate Principles in the Policy; however, they are sufficiently integrated that they were considered together in the Plan.

by the various departments and agencies that are addressing the R&D goals and objectives. In addition, this Technical Appendix contains 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.

To conduct this preliminary assessment of opportunities, a methodology was developed to consider four key issues:

- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the near term;
- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the mid to far term;
- The level of coordination among executive departments and agencies; and
- The level of redundancy of efforts among executive departments and agencies.

Each of these four areas was given a broad assessment of green, yellow, or red based on this review. A green assessment denotes that R&D activities planned or ongoing are sufficient to achieve the objectives in the time frame indicated, that there is strong coordination among executive departments and agencies, and that there is no unnecessary redundancy. A yellow assessment indicates that R&D activities should provide significant progress toward the objectives but there is some risk due to fiscal or other constraints that merits continued attention, that coordination is taking place but could be improved, or that there does not appear to be unnecessary redundancy but additional coordination may be warranted. A red assessment highlights an area where additional emphasis or improved coordination among executive departments and agencies may be warranted to achieve the objective.

This Technical Appendix is the result of an interagency effort coordinated by the Aeronautics Science and Technology Subcommittee (ASTS) of the Committee on Technology of the National Science and Technology Council. ASTS representation included membership 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 (EPA), the Federal Aviation Administration (FAA), the Joint Planning and Development Office (JPDO), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the National Science Foundation (NSF).

It is envisioned that this Technical Appendix will serve to support informed discussion of aeronautics R&D across the aviation enterprise, enhance interagency coordination, and help facilitate the biennial updates to the Plan as required by EO 13419.

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 AND BACKGROUND

Mobility through the air is a key function of the nation's air transportation system. The industry contributes an estimated $640 billion to the U.S. economy or roughly 5.4% of the nation's gross domestic product.[7] Over 9 million jobs with $314 billion in wages are estimated to be associated with the industry. Aerospace, the third largest U.S. export category and largest manufacturing sector exporter, contributes a net surplus of approximately $36 billion to the U.S. trade balance.[8] 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,[9] as well as passenger and cargo capacity projections.[10] A healthy, innovative aeronautics enterprise pursuing new civil aircraft and air traffic management technologies, such as those envisioned in the National Plan for Aerospace Research and Development and Related Infrastructure (Plan) approved in December 2007, will both support air mobility in the United States and strengthen the economy by creating U.S. jobs.

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 108-76). The law established the JPDO, representing six Federal Government departments and agencies and the private sector, to develop the Next Generation Air Transportation System (NextGen). NextGen is envisioned as a revolutionary transformation of the U.S. airspace system to a performance-based, scalable, network-enabled system that will be flexible to

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[7] This estimate includes indirect and secondary impacts (such as visitor expenditures and other economic activity generated by aviation). Source of estimate: http://www.faa.gov/ regulations_policies/reauthorization/ change_needed/.

[8] http://www.faa.gov/regulations_policies/reauthorization/change_needed/.

[9] By 2025, the possibility exists that new aircraft with significant changes in their performance capabilities will join the fleet (e.g., blended wing body [BWB] aircraft, supersonic business jets, small transports and advanced rotorcraft).

[10] The National Airspace System (NAS) needs to accommodate, according to estimates, between two (2×) and three times (3×) the number of operations (where operations are defined as takeoffs and landings) by 2025 compared with levels in 2004. The general aviation fleet is forecast to grow more than 20% during the next 10 to 15 years. Commercial enplanements are forecast to grow by factors ranging from 1.8 to 2.4 times 2004 levels by 2025 (FAA Terminal Area Forecast 2007–2025; Boeing 2007 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).

adapt to meet future air traffic needs. The NextGen vision relies on satellite-based navigation, surveillance, and networking. Investments in new technology provide the means to move from today's human-centric, tactical, centralized command-and-control system to a more automated, decentralized, strategic air transportation management concept. Improved weather information, available when and where it is needed, will enhance safety and contribute to greater system capacity and throughput in all weather conditions.

There are clear signs today that the nation's air traffic management system is under serious stress as a result of current demand levels in many metropolitan areas. The potential effects of global warming, coupled with the projected growth in air transportation, have triggered concerns over aircraft noise and emissions. While the 2007 and 2008 fuel price increases have led airlines to reduce capacity and to take some of the oldest (also noisiest and least fuel efficient) aircraft out of service, delays continue to persist. Delays result in a large cost to industry, passengers, shippers, and government. As part of near-term efforts, the FAA has proposed market-based, economic solutions to reduce congestion in the New York metropolitan area, but these are being met with opposition from airlines and local airports. Even if such potential near-term solutions are successful, current demand projections still point to the need for a fundamental transformation of the National Airspace System (NAS) to enable long-term growth.

Achieving NextGen will require focused and coordinated R&D to address key decisions and challenges associated with system transformation. The R&D goals and objectives relevant to this transformation were identified in the Plan. The capabilities of the envisioned system are network-enabled information access; performance-based services; weather assimilated decision-making; layered, adaptive security; position, navigation, and timing services; trajectory-based aircraft operations; "equivalent visual" operations; and "super-density" operations. The Plan also identified goals and objectives for aircraft that were envisioned in the 2025 time frame and beyond and the means for integrating them into the NextGen environment to take full advantage of their anticipated capabilities. These aircraft represent advances in aircraft designs, materials and structures, and propulsion systems for both subsonic and supersonic flight. It is important that the new vehicle component technologies and vehicle concepts be introduced in a timely manner with a faster and less costly certification process.

Domestic and international environmental pressure may, in the long term, diminish the currently unconstrained projection of air traffic growth, but significant advances in research in environmental technologies (described in the Energy and Environment section of this Technical Appendix) will serve to counter such pressure. A recent study of the projected 2025 U.S. airport capacity[11] indicates that, with implementation of most NextGen capabilities that will lead to airport capacity improvement, there will still be 8 metropolitan areas and 14 airports with insufficient capacity to meet current demand projections. This capacity shortfall points to a need to explore which market-based, economic solutions work under what circumstances and to find politically acceptable means for implementing workable solutions.

The following sections define an action plan to ensure the vitality of mobility through the air for the nation. They include a delineation of the current state of the art including critical challenges, approaches to meeting these challenges, and a preliminary assessment of current relevant federal aeronautics R&D activity. Finally, an analysis of areas of opportunity for potential increased emphasis and potential areas of unnecessary redundancies is conducted.

STATE OF THE ART

Today's 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 these procedures remain largely unchanged despite new concepts of operation afforded by current and near-term technologies. The NAS is built around human operators; hence cognitive human limitations restrict the number of aircraft an individual air traffic controller can handle. The NAS is a highly procedural system, designed to overcome human limitations in dealing with the complexity of the busy airspace/airport network.

The resulting inefficiencies pose cost and capacity limitations on aviation growth. Due to the rigidity of the existing airspace structure, the options available to re-route flows of aircraft to accommodate significant changes to the operating environment (e.g., convective weather, shifting winds, and unpredictable aircraft trajectories) are often limited. Such limitations create restrictions that typically result in airborne and ground delays as well as an inability to accommodate user preferences. In addition, overly conservative interpretations of uncertainties in weather forecasts result in inefficient use of available NAS resources. Hence, pilots cannot make effective tactical flight-path decisions because they have insufficient weather information in the cockpit. Such uncertainty is managed by queuing air traffic waiting to be serviced, and demand is managed by restricting aircraft access to the airspace to avoid straining capacity. Disruptions, increased cancellations, and inefficient use of available NAS resources result from decisions based on uncertain forecasts. Unnecessary flight delays result from inefficient aircraft routing around "choke points" and regions of

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[11] *Capacity Needs in the National Airspace System 2007-2025 – An Analysis of Airport and Metropolitan Area Demand and Operational Capacity in the Future*, FAA, May 2007.

dangerous weather, and from suboptimal recovery from weather anomalies and other system disruptions. Flight planning takes weather prediction into account, but it is inadequate to efficiently deal with the ever-changing weather disturbances that actually develop.

Aircraft traffic flow management is designed to work with today's airspace operations. Current techniques are not well suited for a system based on four-dimensional (4D)[12] trajectories and potential trajectory contracts between an Air Navigation Service Provider (ANSP) and the aircraft.[13] Aircraft operations are limited to the performance of the legacy fleet and new avionics will be required to support technologies necessary to increase capacity. However, there are neither clear incentives nor policies for equipage.

Today's weather observations and forecasts provide general information that must be applied over differing geographic scales and timelines to support aviation operations. Because this weather information is not tailored to specific decisions, it is not sufficient in accuracy, timeliness, detail, and resolution to support the trajectory-based, high-density, and tactical separation operations envisioned with NextGen. Weather information from different sources also results in uncoordinated decision-making by key stakeholders (e.g., flight operations centers, pilots, controllers, and traffic managers). Today, ANSPs and users have various decision-support capabilities that assist in flight planning and execution. A drawback is that weather information is mostly limited to text and graphics that must be interpreted and integrated manually with flight information, giving rise to inefficient, inconsistent, and unpredictable decisions.

On the airport surface, runway incursions and missed taxi clearances result from a lack of shared situational awareness by pilots and/or controllers. Runway incursion prevention systems have limited effectiveness. Ground support equipment operates according to prescribed procedures, but there is no active monitoring of movement of the equipment. Constraints on information exchange between flight crews, the ANSP, and ramp management result in inefficient traffic flows on the airport surface. Ground surveillance available to the ANSP is limited. There is essentially no cockpit surveillance of other ground traffic/vehicles, except by visual observation (out the window). Aircraft surface movement information (e.g., push-backs, departures, taxi delays, etc.) is generally not integrated with traffic flow management.

Most airports are publicly owned and operated by a city, county, or airport authority. Different airports in a region are often owned and operated by different local governments that may have differing objectives. Regional considerations are not typically part of the master planning process, due in part to jurisdictional boundaries. There are many non-towered

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[12] Latitude, longitude, altitude, and time.

[13] This is generally called a "4D trajectory-based system."

airports with limited capacity for controlled traffic due to inefficient one-in-one-out operations. The terminal building and surrounding airfield are static, with considerable work and disruption required to accommodate changes and new developments. Passenger flow at many airports is slow and cumbersome at best. Defined standards are used to guide airfield design, as appropriate for today's aircraft and operational procedures. The ground transportation system is based primarily on private automobiles, rental cars, and taxis, resulting in limited opportunities for inter-modal connections.

Today's aircraft operate under current, often inefficient, procedures that are very similar to those created decades ago. Without updating those procedures NextGen will be prevented from attaining capacity and safety goals while significantly decreasing the environmental footprint of aviation. The projected improvements in the capacity and safety of the air transportation system are largely based on the application of modern procedures to an incremental evolution of the fleet. However, a number of dramatic improvements in future aircraft (e.g., cruise-efficient short takeoff and landing [STOL], advanced rotorcraft, very light jets, or even supersonic vehicles) can have a significant effect on the capacity and environmental impact of NextGen while maintaining or improving the safety of the current system. Future introduction of such vehicles into the fleet mix will be challenging due to the changes in the characteristics and performance of these aircraft compared with those of today. If the new capabilities of these vehicles cannot be fully exploited in the future air transportation system, the United States will lose the potential benefits that such advanced aircraft would bring. Therefore, it is important that these aircraft be developed with full consideration of the capabilities of NextGen. Likewise, NextGen must be developed in such a way to accommodate advancements expected in future aircraft.

FUNDAMENTAL MOBILITY CHALLENGES TO OVERCOME

Shortfalls associated with the state of the art will have to be overcome to achieve increased mobility during the decades ahead. The following major mobility challenges were identified in the Plan:[14]

1. 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.
2. Dynamically balancing airspace capacity to meet demand by allocating airspace resources and reducing adverse impacts associated with weather.
3. Developing more accurate and timely observations and forecasts of aviation-relevant weather to enable NextGen.
4. Increasing airport approach, surface, and departure capacity.

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[14] The challenges listed within this chapter of this Technical Appendix are listed according to their appearance in the Plan. No prioritization or ranking is implied or intended by the order of presentation within the Plan or this Technical Appendix.

5. Developing airport terminal designs that facilitate passenger throughput, including movement between surface and air transportation modes.
6. 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.
7. Improving the efficiency and performance of all classes of aircraft to take advantage of improved methods of operating aircraft within the NAS.
8. 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.
9. Understanding enterprise-level issues (e.g., environmental, organizational) and interactions critical to successful transformation.

The bulk of the required aeronautics research identified in the Goals and Objectives table (Table 2) will address the mobility challenges associated with airspace, weather observations and forecasts, airports, and aircraft. Challenges related to human-machine integration cut across the airspace, weather, airports, and aircraft areas and must therefore be addressed as an integral part of R&D in each of these. Finally, R&D is needed to address enterprise-level issues. Table 1 shows which mobility challenges apply to each of these six areas. Approaches to meeting the challenges in each area are examined briefly below.

Table 1. Mapping Mobility Challenges to Research Areas

	Airspace Goals 1 & 2	Weather Goal 3	Airport Goal 4	Aircraft Goal 5
Challenge 1	x			
Challenge 2	x			
Challenge 3		x		
Challenge 4			x	
Challenge 5			x	
Challenge 6				x
Challenge 7				x
Challenge 8	x		x	x
Challenge 9*				

**Note: Challenge 9 is discussed on page 23, see “Meeting Enterprise-Level Challenges.”*

Meeting Airspace Challenges

Mobility in the 21st century will require increased capacity and controller productivity and decreased aircraft operations costs. The NAS is a complex network of systems on which the demand for movement of people and goods must be balanced with the supply of system resources such as airspace and runways. To overcome today’s procedural limitations it will be necessary to move to more intelligent automation and to shift the controller's role from tactical aircraft separation responsibilities to strategic flow management. A major challenge will be to design the future system for balanced roles for people and automation in a manner that preserves the current high safety standard. To achieve reduced aircraft separations it will be necessary to develop automatic conflict detection and resolution algorithms, trajectory analysis methods, and system architectural characteristics that together result in automated resolution trajectories that are safe, efficient (i.e., airspace and user preferred), and robust under the wide variety of traffic conditions and airspace characteristics. Safe and efficient trajectory-based operations must be achieved under the complex interactions of multiple aircraft turning, climbing, cruising in level flight, descending and merging in ever-changing wind, weather, and visibility conditions. This must be accomplished while ensuring the ability to safely adjust for unforeseen events such as deviating aircraft or data-communications failures. It is anticipated that, for operational acceptance and interoperability with tactical safety assurance functions, an automated resolution system capable of detecting and resolving nearly all projected traffic conflicts 5 to 15 minutes prior to loss of separation (depending on traffic conditions) must be developed.[15] Promising approaches include global trajectory optimization, closed-form analytical methods, and rule-based heuristic search methods.

As traffic demand increases, new approaches to separation management at the busiest airports and in dense terminal airspace must be explored. There must be simultaneous satisfaction of precision sequencing, merging, spacing, and de-confliction requirements while meeting environmental constraints. The degrees of freedom for possible solution spaces become limited when one takes into consideration the wide range of performance capabilities of aircraft expected to fly in tomorrow's aviation system.

New ways are needed to manage traffic flows to maintain maximum capacity when there are system disturbances and to recover from those disturbances with minimal impact on the overall airspace network. System capacity increases may be met by dynamically restructuring the airspace, by dynamically allocating human resources such as controllers, and by promptly communicating system status to all users. High-density traffic flows especially need to be resilient against off-nominal conditions, such as an aircraft deviating from its assigned trajectory. This may require a balance between eliminating all predictable sources of variance in traffic spacing and maintaining sufficient margin in traffic flows to adjust to unexpected circumstances. Airspace configuration restructuring to adjust capacity to demand will have to interact with a traffic flow management function on multiple temporal scales: annual, seasonal, monthly, weekly, and daily. Integration of weather data into information that is tailored to specific air transportation management decisions

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[15] Any solution to a conflict between two aircraft should not create a conflict with another aircraft (includng aircraft in restricted or special use airspace) in the 5–15 minute window.

and that is sufficient in terms of accuracy, timeliness, detail, and resolution is a key challenge for enabling strategic balancing of demand and capacity within the trajectory-based airspace system.

Meeting Weather Observation and Forecast Challenges

The NextGen vision is characterized by more accurate, more timely, more detailed, and higher resolution weather information. The fidelity of weather observations and forecasts will need to match operational needs. Forecasts that include probabilistic information are needed to enable more efficient air traffic management and planning decisions, including improved collaborative operator and service provider flight planning. NextGen will require a common weather picture for all aviation users and this information will have to be shared across multiple organizations, available when and where it is needed. Weather information will need to be seamlessly and automatically integrated into operations and decision-support tools, overcoming limitations of human interpretation.

A 4D space-time weather cube that includes NextGen weather observations and forecasts as well as forecaster tools will be required. The multiple sources of weather information in the cube will have to be fused into a Single Authoritative Source to give users and ANSPs a common weather picture. Decision support tools to deal with weather issues will require the use of this common weather picture. The tools will have to identify risks associated with weather phenomena, suggest strategies for overcoming the risks, and help minimize weather-related user disruptions. Decision support tools must be able to identify aircraft trajectories that maximize safety, schedule, efficiency, and environmental impact requirements. Weather services are expected to be tailored to support trajectory-based procedures. Weather information from the 4D cube will have to be "published," users will need to "subscribe" to pertinent information, and advisories are expected to be broadcast to all through a net-centric information system. Weather information in the cube will need to be updated rapidly and automatically from multiple weather sources, including network-enabled aircraft that collect and transmit airborne observations.

Meeting Airport Challenges

Airports of the 21st century will need to have greater capacity, lower operations costs, faster passenger and cargo throughput, and will have to support improved quality of air travel. Airports, as a central link in the air transportation chain of operations, determine the total capacity of the air transportation system. Achieving significant capacity gains will require maximizing the use of existing airport infrastructure, through both increased use of smaller airports and new procedures that increase runway throughput. Meeting the projected air traffic demand increases at the busiest airports and in dense terminal airspace will necessitate new approaches to separation management. Achieving the necessary airport approach, surface, and departure capacity will require greater involvement of the cockpit crew and avionics. New systems and procedures will have to bring operations during poor weather to the same level as during good weather conditions. General aviation (GA), to be better served, will need greater access to large airports, improved operations in poor weather at small airports, and policies to preserve small airports. Current projections are that, even with the improvements made possible by NextGen, there will still be a capacity shortfall at some of the nation's major airports. Thus there will be a need for regulatory or market-based mechanisms to manage congestion when airport capacity is not sufficient. Finally, outreach programs and best management practices are required to enhance community understanding and support for the expansion of the nation's primary and secondary airports because, unlike other components of the air transportation system that are directly managed by the Federal Government, primary decision-making for airports is at the local level.

Low visibility is very disruptive to airport operations. Surface traffic is impeded because aircraft cannot safely navigate and tower personnel cannot effectively monitor traffic during these conditions. Greater traffic on ramps and taxiways increases the need for more effective monitoring of aircraft and surface vehicle movement to ensure safety levels are maintained, regardless of the visibility conditions. NextGen will have to minimize the disruption of weather on all aspects of surface operations and safely maintain departure and arrival rates in low visibility conditions. Systems will have to be developed to increase operator and controller situational awareness in low visibility conditions to increase surface movement efficiency. This will require special attention to appropriate human-machine interactions in a highly automated airport environment.

Airports that are currently operating at or near maximum capacity will only be able to adapt to increased demand by increasing the efficiency of operations and/or addressing capacity constraints by infrastructure additions or improvements (e.g., runways, gates, etc.). To address this issue, NextGen will have to improve high-density arrival and departure flows, reduce arrival and departure separations, and permit use of more closely spaced parallel runways. A key component required for increased capacity in terminal airspace is the reduction of the impact of wake turbulence on aircraft separation. A more thorough understanding of wake turbulence propagation and decay can potentially allow for decreased separation standards and subsequent increased throughput for single and multiple runways.

When airports are close to one another, arriving and departing traffic from one of the airports can interfere with traffic flow to and from the others. This results in limiting throughput from a regional perspective. As demand grows, it is expected that the number of closely grouped pairs (or sets) of airports will grow as well. This increases the importance of effectively dealing with the issue of managing departure and arrival flows for metroplex areas and improving the traffic flows of aircraft to and from proximate airports.

Integrating future aviation and surface transportation capabilities and benefits will necessitate coordination across the Department of Transportation and other D&A. Today, airport access is gained primarily via private automobiles, rental cars, and taxis. There are limited opportunities for multimodal connections, often leading to heavy curbside volume and roadway congestion. As airspace and airport capacity are increased, airport access will become a major constraint on the future growth of the air transportation system. In major metropolitan areas the increased use of secondary airports to augment the primary airport(s) is envisioned as a critical component to increase the total system capacity. An essential feature of this projected metro complex is a ground transportation system that will be able to provide effective multimodal transportation throughout the complex and surrounding metropolitan area.

Meeting Aircraft Innovation Challenges

The 21st century will see an increased demand for a variety of classes of aircraft that can deliver the necessary levels of performance (e.g., fuel burn, range, speed) required by the marketplace. These aircraft will have to be safe, have low noise and emissions, have low operating and maintenance costs, and be certified through faster and less expensive processes. Challenges range from predicting the performance of these vehicles before a development decision is made, to the R&D of component technologies that can realize the necessary performance improvements. Much of this work is addressed in the Energy and Environment section of this Technical Appendix and leverages efforts described in the National Security and Homeland Defense (NS&HD) section. However, an understanding of the potential contributions of these vehicles and component technologies to improved capacity and safety and to reduced fuel use must be gained within the context of the air transportation system in which these new vehicles will fly.

New aircraft concepts providing enhanced performance in terms of fuel burn, noise, emissions, and takeoff and landing field lengths are expected to differ from traditional tube-and-wing configurations. A key challenge will be credibly predicting the performance of such revolutionary concepts. In addition, in order to realize practical supersonic vehicles (e.g., business jets or even mid-size transports), a number of R&D issues need to be addressed, including those involving efficiency (e.g., supersonic cruise, light weight, and durability at high temperature); environmental challenges (e.g., airport noise, sonic boom, high altitude emissions); performance challenges (e.g., aero-propulso-servo-elastic design, cruise lift-to-drag, and takeoff and landing constraints); and integration and multidisciplinary analysis and optimization (MDAO) challenges. Many of the technologies for lower noise, lower emissions, and higher performance developed for subsonic/supersonic flight are also anticipated to have a significant impact on future high-performance rotary wing vehicles. Higher performance for rotorcraft will include improved speed, range, payload capacity, and more robust control systems for safer operations. To support the design of new aircraft it is necessary to develop knowledge, data, capabilities, technologies, and design tools for N+1, N+2, and N+3 generations of advanced vehicles.[16]

To fully benefit from the potential of future generation aircraft, new component technologies and vehicle concepts will have to be introduced into the system in a timely fashion. This requirement includes both the development and manufacture of the advanced vehicles themselves and the process of certification of such vehicles and their component technologies. The vast majority of the analysis and design tools that are expected to be developed to facilitate the introduction of advanced vehicle classes into the fleet carry the inherent requirement that the appropriate designs and trades be accomplished with higher fidelity and shorter cycle times. Thus, modern analysis and design tools should contribute to a reduction in the time to design and manufacture both vehicles and components of these vehicles. Changes in certification also have the potential to decrease cost and the time to introduce new aircraft and aircraft subsystems without compromising safety. In the near term, one can take advantage of the increased reliability of commercial electronics. For the mid term, the potential of improvements in aircraft production and in software development methodologies, including verification and validation techniques, needs to be explored. In both the mid and far terms, advances in fault detection, self-diagnostic, and self-healing capabilities in aircraft systems have the potential for significant changes in certification and in maintenance strategies. Advanced materials may also provide greatly improved fatigue lifetime. These capabilities offer the potential for less stringent (and therefore faster and less costly) initial certification requirements and a move away from periodic maintenance requirements to a strategy where maintenance is based on an assessment of the health of individual components and subsystems.

Meeting Human-Machine Integration Challenges

A new role for people, greater use of and more intelligent automation, and a shift of some of the current ground functions to the cockpit offer the potential to overcome the procedural limitations of today’s air traffic management system and, as a result, offer greater capacity and lower cost to aircraft operators and service providers. Humans have always been integral to aviation safety and performance, and will continue to be, even as automation steadily increases. With NextGen capabilities, humans’ duties will potentially transition from tactically separating aircraft to dealing with more strategic problems (e.g., planning, traffic flow management, etc.). Their activities will also need to change in response to the implementation of automation. For example, while automation may off-load some func-

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[16] Future generations of advanced aircraft with enhanced capabilities are described using the following notation: “N” refers to the current generation of tube-and-wing aircraft entering into service roughly 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 2015–17; “N+2” refers to advanced aircraft in the generation after “N+1” that are likely to use revolutionary configurations (such as hybrid wing-body, small supersonic jets, cruise-efficient short takeoff and landing, advanced rotorcraft) that are expected to enter into service, market permitting, in the 2020–25 time frame (with potentially military or cargo applications at first); “N+3” refers to the generation of aircraft after “N+2” with dramatically improved performance and reduced noise and emissions that would be expected to enter into service in the 2030–35 period.

tions from the human, interacting with it and monitoring its performance demands new activities from the human. This interaction needs to be defined with care as automation often lacks transparency. That is, it does not reveal to human operators its internal processes, its knowledge about the state of the system, and what are its actions or plans. Defining an appropriate role for humans in systems that have sophisticated automation of functions that are beyond the anticipated capability of the human alone will be a major challenge. Humans will have to play a role in detecting automation failures and in recovering from such failures, but new concepts must be developed in a way that never puts humans in an untenable situation.

Research to design appropriate roles for humans and machines, both under normal and off-nominal (especially failure) situations, must take advantage of the growing body of existing knowledge of designing for effective human-machine interaction. The proper roles are highly dependent on the specific operating concept and therefore must be addressed as an integral part of NextGen concept research. As the roles of humans and automation are postulated, simulation and analysis must explore the robustness of these roles under all conditions. Emphasis must be placed on a design that permits people and machines to work together to determine that portions of the system are failing and to develop failure recovery methods that are safe.

Meeting Enterprise-Level Challenges

The air transportation system is a complex system of systems that involves multiple technologies, organizational structures, behaviors and cultures, and competing economic entities. The transition from the current to the future air transportation system is expected to involve changes in all of these areas. Better understanding of enterprise-level issues (e.g., environmental, political, institutional, and managerial) is critical to the successful transformation of the air transportation system. A better understanding of the nonlinear, complex, adaptive nature of the airspace system will enhance the ability to analyze, simulate, and model all aspects of system-wide performance and risks associated with the transformation of the aviation enterprise. It will also be necessary to learn how to best deal with resistance to change with a sufficient understanding of the interests of all the stakeholders and to enable and facilitate compromise solutions without which the transformation might be interminably delayed.

SUMMARY OF R&D ACTIVITIES SUPPORTING MOBILITY GOALS

Primarily the FAA and NASA perform R&D for Mobility Goals 1, 2, and 4.[17] FAA activities tend to fall into the applied research and demonstration/development areas, while NASA's focus is on earlier stages of research with significant overlap in applied research to ensure successful transition. NASA also plays a key role in supporting the FAA in large scale concept demonstrations. Goal 3 R&D is performed primarily by the Department of Commerce (DOC) and the FAA with some support by the Department of Defense (DOD) and NASA. Goal 5 R&D is performed primarily by NASA with some support by the FAA.

Goal 1 – Develop reduced aircraft separation in trajectory- and performance-based operations

Goal 2 – Develop increased NAS capacity by managing NAS resources and air traffic flow contingencies

Many of the underlying technologies for Mobility Goals 1 and 2 are common or very closely related, thus the R&D discussions for these goals are combined. Mobility Goals 1 and 2 and associated objectives represent a progression of NextGen capabilities over time, with research performed primarily by NASA and the FAA. Much of NASA's work is in support of mid- and far-term objectives with primary focus on foundational research that advances the state of the art in underlying scientific understanding, identifies promising new concepts, and shows initial concept feasibility. FAA R&D falls primarily into the applied category to support near-term objectives, but also includes foundational human factors R&D and extensive human-in-the-loop simulation and field trials of more mature technology.

NASA R&D addresses the fundamental air traffic management research needs for NextGen by developing revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency, and flexibility of the NAS. Integrated solutions for the allocation of ground and air automation concepts and technologies are being explored. Areas of interest include several functional thrusts: dynamic airspace configuration, traffic flow management, separation assurance, and super-density operations. Crosscutting research to support these thrusts addresses trajectory prediction, synthesis and uncertainty, performance-based services, and the development of system-level design, analysis, and simulation tools.

Dynamic airspace configuration addresses the demand/capacity imbalance problem by exploring ways to increase capacity through dynamic allocation of airspace structure and controller resources. Traffic flow management works to effectively allocate demand

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[17] Regarding Goal 1, there is a potential for technology transfer from DOD to civilian agencies from research on aircraft operations (including those for UAS) in areas such as dynamic air battle-space management.

through departure time and route modification, and through adaptive speed control in the presence of uncertainty. Separation assurance research aims to ensure efficient arrival capacity through traffic sequencing, spacing, and merging, with appropriate separation for transition and cruise airspace, taking traffic flow management goals into account. Airspace super-density operations will be improved through simultaneous multi-objective (e.g., environment, throughput, user preferences, etc.) sequencing, spacing, merging, and de-confliction of aircraft with different performance characteristics for complex terminal airspace. A major objective in all of these research activities is to reduce the capacity-limiting impact of human-controlled separation assurance.

Research into trajectory prediction and synthesis will lead to more accurate trajectory predictions that are interoperable with aircraft flight management system trajectory generation, taking prediction uncertainty growth and propagation into account. To pave the way for performance-based services, research will focus on the performance-enhancing effect of emerging airborne technologies on solutions to fundamental air traffic management problems. Finally, system-level design, analysis, and simulation tools will be developed to assess the functional/temporal distribution of authority and the responsibility among/between automation and humans and to support detailed concept design for nominal and off-nominal design conditions.

NASA conducts Goal 1 research in the following Focus Areas[18] of the Airspace Systems Program: *separation assurance; super-density operations; performance-based services; trajectory prediction, synthesis and uncertainty;* and *system-level design, analysis, and simulation tools.* For Goal 2, NASA conducts research in the following Focus Areas of the Airspace Systems Program: *dynamic airspace configuration; traffic flow management; performance-based services; system-level design, analysis, and simulation tools;* and *coordinated arrival/departure operations.*

The FAA's R&D is exploring implementation issues related to aircraft self-separation. Airspace redesign is being explored to improve efficiency and add flexibility to the air traffic control system. Work is underway to validate mature operations concepts to pave the way for major investment decisions. Studies and experiments explore issues related to integration of uncrewed aircraft systems (UAS) into the NAS. Human factors research is aimed at managing human error hazards, their consequences, and recovery methods in early stages of system design or procedure development, and at assessing concepts and technology to modernize workstations, improve controller performance, and reduce staffing requirements. The FAA's human factors R&D addresses both the controller and pilot sides of the air-ground integration challenge (i.e., the challenge of ensuring that the right information is provided to controllers and pilots at the right time, to make the right decisions).

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[18] NASA's Airspace Systems Program is organized into Research Focus Areas.

The FAA, with support from NASA, the DOD, the DOC, the Department of Homeland Security (DHS), and industry partners, also conducts demonstration projects to support concept validation and to reduce implementation risk. These include joint network-enabled operations demonstration, oceanic trajectory-based operations demonstration, advanced oceanic technology and procedures demonstration, weather prediction integration into the Traffic Management Advisor demonstration, and UAS NextGen integration demonstration.

The FAA addresses Goal 1 objectives in the following Solution Sets:[19] *initiate trajectory-based operations; increase arrivals/departures at high-density airports; increase flexibility in the terminal environment;* and *increase safety, security, and environmental performance.* For Goal 2, the FAA addresses the related objectives in the following Solution Sets: *initiate trajectory-based operations, improve collaborative air traffic management*, and *reduce weather impact.*

Goal 3 – Reduce the adverse impacts of weather on air traffic management decisions

Primarily the FAA and the DOC perform R&D for Mobility Goal 3, although some potential contributions are available from NASA and the DOD. The FAA's weather research portfolio deals with advancing the state of the art in observing and forecasting aviation-hazard-specific atmospheric phenomena, and the means to display such information, typically designed for human end-user interpretation. DOC research is broader in scope, advancing general principles of numerical weather prediction, weather information dissemination, and data storage/archival. The DOC is leading the development of the 4D weather cube, and the FAA will integrate this into its decision-support systems. NASA research is focused on enhancing environmental observation capabilities from ground- and space-based sensors. The DOD conducts research into weather data standards and integration of weather information into mission planning systems. Finally, space weather can have a significant effect on aviation communication, navigation, and radiation to passengers and crew members. Work is ongoing at NASA and DOC, with some support from the DOD, to better predict and specify the radiation environment, characterize the expanse and time duration of the affected area when radio blackouts occur, and predict and specify the ionospheric total electron content that impacts GPS-aided navigation. Trajectory planning tools to develop safer flight trajectories will use this information.

DOC R&D is directed at advancing general weather sensing and forecasting capabilities that can be applied to aviation interests. DOC addresses Goal 3 objectives in *4D Weather Information Data Base* and in *Advanced Weather Interactive Processing System* activities. Significant effort is aimed at developing and implementing better weather sensors to measure standard meteorological parameters such as temperature, pressure, and wind throughout the atmosphere

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[19] The FAA NextGen Implementation Plan is divided into Domains and Solution Sets that group related transformative activities. There are three domains: Air Traffic Operations, Aircraft and Operator Requirements, and Airport Development. Under the Air Traffic Operations domain there are seven solution sets.

from ground-, air-, and space-based observation platforms. DOC supports both polar-orbiting and geostationary satellite constellations that provide near-real-time aviation system-wide coverage. DOC also supports research to advance numerical weather prediction capabilities, from actual physical forecast algorithms to advanced high-performance computer modeling architectures. These core modeling capabilities provide the basis for the research activities by other federal agencies. Finally, DOC conducts research to identify where and when human forecaster intervention into highly automated forecast routines provides the most value.

The FAA's weather R&D portfolio includes a variety of activities designed to better observe and forecast atmospheric parameters (e.g., convection, turbulence, and icing), which are considered direct aviation hazards. The FAA addresses Goal 3 objectives in the *reduce weather impact* Solution Set and is advancing the knowledge of the basic underlying physics of weather phenomena in order to advance computer forecast modeling techniques. In addition, the FAA is developing better systems and display devices to convey weather situational awareness to human end-users (e.g., controllers, dispatchers, and pilots). Human factors research at the FAA is aimed at understanding how humans (on the ground and in the air) interpret meteorological displays and at how those interpretations affect overall workload and performance. In the near term, the FAA will be conducting a demonstration focused on integrating weather prediction into the Traffic Management Advisor. Also, many of the FAA concept-validation and risk-reduction demonstrations (listed elsewhere in the Mobility section) have a weather aspect.

NASA R&D does not explicitly address improving aviation weather forecast technology; however, there is significant research to improve the ability to observe and monitor the state of the atmosphere from ground-, air-, and space-based platforms. In addition, NASA invests in database technologies that will contribute to the overall success of the 4D weather cube. This research is conducted as part of NASA's Earth Science Program.

DOD R&D is focused on integration of weather information into automated military decision-support systems. Two particular DOD activities have the potential to contribute to NextGen weather capabilities. The DOD has developed a standard communications protocol for disseminating weather information and has made considerable investments in applying weather information into warfighting mission planning systems.

Goal 4 – Maximize arrivals and departures at airports and in metroplex areas

R&D for Goal 4 is performed by NASA and the FAA, with roles and responsibilities similar to those for Goals 1 and 2.

In support of Goal 4, NASA will continue to explore concepts and technologies aimed at increasing the capacity, efficiency, and flexibility within the airport and terminal domains.

The R&D program will address safe and efficient surface operations and coordinated arrival/departure operations. In support of these, NASA will conduct system analyses of airport constraints and benefits.

Surface operations research will explore trajectory-based automation technologies to optimize ground operations, 4D taxi clearances and conformance monitoring, and runway incursion prevention. Coordinated arrival/departure operations research will lead to improvements in the capacity of both individual runways and multiple runway systems. This includes research into runway scheduling and balancing and wake vortex prediction science to support NextGen super-density operations. NASA will model airport and terminal area environmental constraints and investigate mitigation options. In support of concept development, the roles and responsibilities of controllers and pilots, controller interface with optimization tools, and integration with airport arrival/departure and metroplex flow planning will be explored. Finally, NASA will conduct systems analyses of airport constraints and benefits, perform research into human/system integration (supported by human performance modeling), and develop concepts for metroplex and regional airport system operations.

NASA conducts Goal 4 research in the following Focus Areas of the Airspace Systems Program: *super-density operations; safe and efficient surface operations; coordinated arrival/departure operations;* and *airport transition and integration management.*

In support of Goal 4, the FAA will continue to conduct research into improving capacity, efficiency, and safety of surface, approach, and departure management for high-density airport, secondary airport, and metroplex operations. Surface management system R&D is aimed at improving situational awareness, supporting surface navigation during inclement weather conditions through the use of ground-based augmentation systems, and achieving a fully collaborative surface environment. The resulting surface traffic plans will be integrated with arrival and departure management. Airport capacity will be increased through the use of required navigation performance (RNP) for arrivals and departures, self-spacing for lateral and in-trail operations, and reducing the negative impact of wake vortices. At lower density (secondary) airports, R&D will result in greater flexibility of operations and more efficient use of airspace and ground assets.

Airport research will explore the use of virtual towers, as well as means to alleviate traffic congestion and system delays through new runways, airport and aircraft technologies, and improved operational procedures. Work is also aimed at improved airport planning, airport design, and longer lasting pavements with lower maintenance needs. Other areas of R&D include the integration of weather information into decision-support tools; the exploration of appropriate roles for pilots, controllers, and dispatchers in NextGen; and safety improvements through conflict detection and resolution for low-altitude and surface operations and Traffic Alert and Collision Avoidance System (TCAS) upgrades.

FAA concept-validation and risk-reduction demonstrations (with support from NASA, DOC, DHS, and industry partners) include a joint network-enabled operations demonstration; arrivals and departures included in oceanic trajectory-based operations demonstrations (at Miami and Daytona Beach); weather prediction integration into the Traffic Management Advisor demonstration; fully collaborative surface environment demonstrations (expansion of the Memphis FEDEX demonstration and surface management ASDE-X[20] demonstration at John F. Kennedy International Airport); a demonstration of integration of multiple airport technologies at Daytona Beach (Embry-Riddle University); continuous descent, tailored arrival, and 3D path arrival management demonstrations; and a low-visibility tower demonstration.

The FAA addresses Goal 4 objectives in the following Solution Sets: *initiate trajectory-based operations, increase arrivals/departures at high-density airports, increase flexibility in the terminal environment, improve collaborative air traffic management,* and *transform facilities.*

Goal 5 – Develop expanded aircraft capabilities to take advantage of increased air transportation system performance

Mobility Goal 5 and its associated objectives represent a sequence of enhancements to the capabilities, performance, environmental compliance, and certification process of future generations of aircraft that will fly in NextGen. The research work to accomplish the objectives is primarily performed by NASA, the FAA, and the aerospace industry.[21] While the DOD focuses on technologies for military aircraft, some technologies may inform or eventually have applications for civil aircraft as well. The achievement of Goal 5 will require R&D into component technologies, revolutionary aircraft configurations and propulsion systems, and the ability to confidently predict their performance.[22]

NASA's primary focus is on advancing the state of the art in physics-based tools to understand the performance and environmental impact of future advanced vehicles. In addition, NASA is carrying out research to define various alternatives for N+1, N+2, and N+3 generations of aircraft that frame the R&D challenges for many of the component technologies. The FAA is responsible for accelerating the introduction of some of these concepts and technologies into the fleet.

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[20] ASDE X, the Airport Surface Detection Equipment, Model X, is a traffic management system for the airport surface that provides seamless coverage and aircraft identification to air traffic controllers.

[21] The role of the aerospace industry is critical in achieving the objectives of Goal 5. It is members of the industry who design and build the vehicle concepts that are demanded by the marketplace and are required to meet regulatory and certification requirements. The aerospace industry invests significant resources in R&D for many of the technologies required to attain Goal 5.

[22] The research in many of the component technologies, especially those aimed at reduced fuel burn, noise, and emissions, is addressed in the Energy and Environment section of this Technical Appendix and will not be repeated here.

In support of Goal 5, NASA will pursue the development of advanced aircraft concepts and technologies that can lead to achieving the overarching goals of NextGen—improved capacity and safety while significantly reducing the environmental impact of aviation. These concepts and technologies are applicable to a broad spectrum of classes of vehicles (N+1 through N+3) and will enable improvements in performance (e.g., fuel burn, takeoff and landing field lengths, and speed and range) and environmental compliance (e.g., noise, emissions, sonic boom, etc.). Because future aircraft are envisioned to be significantly different from today's aircraft, the development of validated physics-based multidisciplinary analysis and design capabilities is necessary. NASA will pursue tools and techniques that will accomplish this objective. In addition, NASA will pursue research on component and system technologies to enable vastly improved aircraft performance.

NASA conducts Goal 5 research in the following Projects of the Fundamental Aeronautics Program: *Subsonic Fixed Wing (SFW), Subsonic Rotary Wing (SRW),* and *Supersonics.* This research includes efforts in support of performance, noise, emissions, and MDAO.

The DOD conducts a wide range of research in aircraft technologies for fixed- and rotary-wing vehicles, UAS, advanced propulsion, and aircraft power. These include novel aircraft configurations for improved efficiency; quieter, more efficient rotorcraft with increased performance; advanced propulsion concepts with dramatic improvements in fuel efficiency; increased power and thermal management capacity; and technologies to enable UAS integration in the airspace. DOD R&D efforts span the range from advanced technology development in the near term to foundational research for future generations of military aircraft. Much of this work is described in the National Security and Homeland Defense section of this Technical Appendix.

In support of Goal 5, the FAA carries out activities in the *Aircraft and Operator Requirements* domain. The FAA is pursuing the improvement of the timeliness of the certification and introduction into the fleet of advanced technologies and concepts for much needed improvements in performance and environmental impact. Better understanding of the requirements for certification of advanced technologies; clear assessments of the impact of advancements in materials, structures, and vehicle health monitoring on the certification process; and an understanding of the level of validation and verification for flight software, as well as software for physics-based predictions, will be needed.

ANALYSIS OF OPPORTUNITIES WHERE ADDITIONAL R&D FOCUS MAY BE WARRANTED

The Mobility aeronautics R&D goals and objectives were assessed in light of the activities described in this Technical Appendix to identify areas of opportunity for potential increased emphasis, as well as potential areas of unnecessary redundancy and the adequacy of coordination across departments and agencies. The results for Goals 1–4 were drawn in part from a gap analysis conducted in early 2008 by the JPDO in conjunction with its member departments and agencies. The methodology for the present assessment considered the previously described four key issues:

- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the near term;
- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the mid to far term;
- The level of coordination among executive departments and agencies; and
- The level of redundancy of efforts among executive departments and agencies.

Each of these four areas was given a broad assessment of green, yellow, or red based on this review. A green assessment denotes that R&D activities planned or ongoing are sufficient to achieve the objectives in the time frame indicated, that there is strong coordination among executive departments and agencies, and that there is no unnecessary redundancy. A yellow assessment indicates that R&D activities should provide significant progress toward the objectives but there is some risk due to fiscal or other constraints that merits continued attention, that coordination is taking place but could be improved, or that there does not appear to be unnecessary redundancy but additional coordination may be warranted. A red assessment highlights an area where additional emphasis or improved coordination among executive departments and agencies may be warranted to achieve the objective. The overall results of this analysis for Mobility are shown in Table 2 at the end of this section.

As shown in Table 2, planned and ongoing efforts are sufficient for meeting all near-term objectives for Mobility R&D Goals 1, 2, 3, and 4, and significant progress toward Goal 5 objectives is expected. In the mid and far terms, activities are sufficient to meet all objectives for Goal 3, and significant progress is expected for all objectives for Goals 2 and 5. Ongoing efforts for the mid and far terms for Goals 1 and 4 are sufficient for meeting some objectives, and significant progress is expected toward the rest. For the objectives marked in yellow, improvements are possible—in some cases with better planning and in others with balancing technical risk against available resources. There is generally strong interagency coordination with adequate processes in place and no unnecessary redundancy for Goals 1, 2, 4, and 5, although interagency coordination could be improved for the first objective of Goal 5. For Goal 3, a yellow rating was recorded because coordination could be improved between departments and agencies and some redundancy exists.

Goal 1 – Develop reduced aircraft separation in trajectory- and performance-based operations

To achieve improvements to mid- and far-term R&D, better focus of FAA R&D on human roles and responsibilities in separation assurance and in trajectory/performance based operations is needed. Avionics upgrades play a crucial role in NextGen, and thus warrant prioritized FAA efforts on 4D trajectory flight management computer upgrades and collision-avoidance paradigm changes (TCAS upgrades). To focus the definition of future Goal 1 concepts, NASA should prioritize R&D efforts in air-ground functional allocation and enhance the collaboration between separation assurance and traffic flow management research. New communication paradigms form the underpinnings of this goal but also present significant challenges. To achieve Goal 1 objectives, the FAA should develop coherent definitions of required data and voice communication capabilities and focus its communications R&D to meet objectives. Finally, greater emphasis is needed to validate NASA algorithms and methods to determine how to safely integrate future communications advancements into the air traffic management system and to transition these new capabilities to advanced systems development.

Goal 2 – Develop increased NAS capacity by managing NAS resources and air traffic flow contingencies

Opportunity exists for additional or enhanced R&D in the area of dynamic airspace operations. The FAA needs to increase efforts to identify how these operations will be managed and NASA must focus on research that supports dynamic airspace in terminal redesign. NASA must increase emphasis on integrating weather information into decision-support tools that are being developed to assist in traffic flow management and to a lesser extent into tools for managing NAS resources. It should be noted that some of the opportunities identified for Goal 1 will support Goal 2 as well.

Goal 3 – Reduce the adverse impacts of weather on air traffic management decisions

The primary opportunities identified to better achieve the Mobility weather goal were in reducing interagency overlaps and in coordination of activities across agencies. Better portfolio definition and integration across agencies is needed. One example is the integration of FAA System Wide Information Management, NextGen Network Enabled Weather, and NextGen Weather Processor to support the 4D weather cube. Another is the integration of DOC observation systems and forecast products for aviation use. To help agencies involved in weather sensor development, the FAA needs to better define future FAA requirements for weather sensors. Research on the use of weather information by aircraft operators and on related avionics at the FAA must be tied more closely to weather plans. Finally, there are opportunities for increased R&D in the space weather area.

Goal 4 – Maximize arrivals and departures at airports and in metroplex areas

Opportunities for R&D improvements were found in surface, arrival, and departure management. Prioritized NASA/FAA R&D would help improve the integration, separation assurance, and capacity of surface/departure/arrival management processes and also place more focus on development of the 4D trajectory departure concept. Wake vortices still represent a major challenge to reducing spacing to increase arrival and departure capacities. While the FAA has increased its efforts to optimize operations within existing wake vortex separation minima, significant R&D on wake vortex encounter dynamics in terminal operations will be required to reduce these minima. Challenges remain with the environmental constraints in the airport vicinity and will require focused R&D to understand the noise and emissions trade-offs of varied departure and descent profiles of current and future aircraft systems.

Goal 5 – Develop expanded aircraft capabilities to take advantage of increased air transportation system performance

The fundamental research base in aircraft-related R&D to support the Mobility Goal is adequate, but opportunities exist for more system-level experimentation at NASA. To enable supersonic flight over the continental United States, especially for small transport-sized aircraft, noise resulting from sonic booms must be significantly reduced. Low sonic boom flight experimentation does not currently exist at NASA. The introduction of new aircraft into the NAS with vastly different performance capabilities may require changes to future NAS planning and regulations if the nation is to benefit from the performance of future air vehicles. Cross-agency programs are needed to assess the viability of introducing a range of new vehicles, including those with specific DOD requirements, into the NAS.

SUMMARY

The JPDO initiatives to foster interagency R&D cooperation and alignment have had a positive impact on Mobility R&D. Three of the most recent initiatives that have contributed to this are the 2008 JPDO gap analysis, the establishment of NASA/FAA Research Transition Teams, and the high level agreements regarding weather technology between the FAA and the DOC. The agreements and processes that the FAA, NASA, DOD, and DOC have put in place will, within available resources, address many of the opportunities for Goals 1–5 identified in this Technical Appendix.

Table 2. Mobility Opportunities Analysis

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)	Near Term Objectives	Interagency Coordination	Redundancy	Mid and Far Term Objectives
Goal 1 Develop reduced aircraft separation in trajectory- and performance-based operations	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	G	G	G	G
	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	G	G	G	Y
Goal 2 Develop increased NAS capacity by managing NAS resources and air traffic flow contingencies	Develop advanced airspace design concepts to support 3× operations Develop Special Use Airspace and GA 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 ANSP negotiations	G	G	G	Y
	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	G	G	G	Y
Goal 3 Reduce the adverse impacts of weather on air traffic management decisions	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	G	Y	Y	G
	Develop initial capability for net-centric 4D 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, 4D weather grids	Develop severity indices for aviation weather hazards to identify adverse weather impact	Reduce adverse impact of weather with NextGen Network-Enabled Weather	G	Y	Y	G

Table 2. Mobility Opportunities Analysis—continued

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)	Near Term Objectives	Interagency Coordination	Redundancy	Mid and Far Term Objectives
Goal 4 Maximize arrivals and departures at airports and in metroplex areas	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	G	G	G	G
	Develop time-based metering of flows into high-density metroplex areas	Develop performance-based trajectory management procedures for transitional airspace	Develop time-based metering for flows transitioning into and out of high-density terminals and metroplex areas to enable significant airspace design flexibility	G	G	G	Y
	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	Demonstrate technologies and procedures to support surface operations	G	G	G	Y
Goal 5 Develop expanded aircraft capabilities to take advantage of increased air transportation system performance	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	Y	Y	G	Y
	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	Y	G	G	Y
	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 STOL 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)	Y	G	G	Y

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

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 NAS 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 continue to advance its technological advantage to retain air superiority in traditional peer-on-peer conflict. Aviation provides for many of the strategic and tactical needs of the warfighter in this environment, including strike; air superiority; command, control, intelligence, surveillance, and reconnaissance (C2ISR); and airlift. However, a number of fundamental challenges stand as barriers to continued technical progress, including lighter, quieter, and more efficient fixed- and rotary-wing aircraft; highly efficient propulsion systems; thermal and energy management; and high-speed and, ultimately, hypersonic flight. In addition, as UAS become integral to military operations, airspace integration and de-confliction as well as cooperative and autonomous control are growing issues affecting not only military operations, but operations in the civil aviation environment as well.

Background—Military and Homeland Defense Capabilities

Aeronautics R&D will continue to provide advanced capabilities for national security and homeland defense. Capability-based planning provides a rational basis and common framework for integrating aeronautics R&D across agencies of the Federal Government. This planning approach links R&D activities and investment with desired end-use capabilities.

Aeronautics R&D can enable new capabilities or provide significant improvements to existing capabilities in the six areas shown in Figure 1. These six aeronautics capability areas, described by their desired end state, cover the spectrum of air domain capability needs for national security and homeland defense:

- Strike/Persistent Engagement—achieve precise and scalable effects from the air with global reach, quick reaction, persistence, and significant payload.
- Air Superiority/Protection—prevent or mitigate an adversary's effect on joint forces and the populations that joint forces protect, ensuring freedom of maneuver.

- Persistent C2ISR—continuously see and understand the battlefield and seamlessly communicate, make informed, timely decisions and synchronize joint actions and efforts.
- Multi-Mission Mobility—move materiel and personnel responsively and efficiently to meet future joint aerial maneuver and lift requirements.
- Responsive Space Access—provide rapid, on-demand access to and from space with flexibility in launch and recovery.
- Agile Combat Support / Enterprise & Platform Enablers—enable full-spectrum system capabilities through design and analysis; modeling and simulation tools, techniques, and processes; and the application, insertion, and integration of technology.

To achieve the desired capabilities, attributes are identified that describe potential ways to achieve these capabilities in terms of their defining characteristics. Each capability area may have multiple attributes, and multiple attributes may be needed to fully realize a capability. Attributes are achieved by the development and demonstration of one or more technology products. Technology products are notional systems or subsystems consisting of an integrated set of key technologies that provide or enable attributes for a capability area. Different technology solutions may represent different approaches to attain an attribute, providing options to the acquisition and user communities.

Capability-based planning is an important construct that enables integration of three important aspects of technology planning. First, the technology products identified in this process provide the basis for establishing technical goals and objectives that drive detailed

Figure 1. National Security and Homeland Defense (NS&HD) Air Domain Capability Areas

R&D planning. This detailed planning results in focused R&D programs to address specific technical challenges. Second, in a resource-constrained environment, capability-based planning provides a rational approach for prioritizing investment based on the link between research efforts and the projected benefits that may be derived. Finally, this construct provides a critical tool for communicating the potential impacts of R&D to key stakeholders. Here, this construct is used to describe national security and homeland defense aeronautics R&D. The relationships between the capabilities in Figure 1 and the following R&D goals and objectives critical to enabling them are highlighted.

NATIONAL SECURITY AND HOMELAND DEFENSE R&D CHALLENGES, GOALS, AND OBJECTIVES

National security and homeland defense aeronautics R&D plans are organized around capability-based planning concepts. However, there are a number of fundamental technical challenges that need to be overcome to enable these concepts. As described in the Plan, these challenges include:

- 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.
- Airspace integration and de-confliction, 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 aeronautics R&D goals were identified to address these challenges. These goals and their associated objectives are provided in the table at the end of this section. In addition to these goals, key research efforts address UAS airspace integration and de-confliction. The next section describes national security and homeland defense aeronautics R&D efforts, showing the relationship between the national security capabilities and these aeronautics R&D goals.

NATIONAL SECURITY AND HOMELAND DEFENSE AERONAUTICS R&D

As described in the previous two sections, technology planning for national security and homeland defense R&D is organized around air-domain capability areas, but several high-level goals are essential to enabling these capabilities. In this section, national security and homeland defense aeronautics R&D activities are described in relation to the capabilities they enable. For each capability area, a mapping is provided that shows the relationship between these activities and the national security and homeland defense R&D goals and objectives. It should be noted that this framework focuses on potential applications for technology, but underlying the technologies described here is a significant body of ongoing research at both foundational and more advanced levels. This research aims at understanding fundamental physical phenomena and exploiting these to further national security and homeland defense capabilities. The technology and knowledge gained from this long-term research feeds into the capability-based plan and enables future capabilities.

Strike/Persistent Engagement

A number of key technologies are required to enable aircraft to achieve precise and scalable effects from the air with global reach, quick reaction, and persistence, while carrying significant payloads. A mapping of the relationship between many of these key technologies and the national security and homeland defense aeronautics R&D goals is shown in Figure 2.

Strike / Persistent Engagement and National Security Goals

Near-Term (0-5 years)

Goal 3: Reduced gas turbine SFC
⇒*Range, persistence, mission flexibility with a single aircraft*
- ADVENT – Design and demonstrate variable cycle propulsion component technologies

Goal 4: Increased power and thermal management capacity
⇒*Decreased time to target and increased sortie rate*
- INVENT – Demonstrate 2X operating temperatures for power electronics

Goal 5: Hypersonic flight
⇒*Rapid response and global reach*
- X-51A – Demonstrate sustained, controlled flight at Mach 5-7 using hydrocarbon fuel

Mid-Term (5–10 years)

Goal 3: Reduced gas turbine SFC
⇒*Range, persistence, mission flexibility with a single aircraft*
- ADVENT – Demonstrate variable cycle propulsion system enabling 25% or greater SFC reduction

Goal 4: Increased power and thermal management capacity
⇒*Decreased time to target and increased sortie rate*
- INVENT – Demonstrate 5X increase in thermal transport and heat flux for power electronics

Goal 5: Hypersonic flight
⇒*Rapid response and global reach*
- Robust scramjet – Ground test scramjets to 10X airflow of X-51A
- Robust scramjet – increase thermal balance point to Mach 8+ on hydrocarbon fuel

Far-Term (>10 years)

Goal 3: Reduced gas turbine SFC
⇒*Range, persistence, mission flexibility with a single aircraft*
- Advanced propulsion concepts with variable cycle features and high overall pressure ratio enabling >30% SFC reduction

Goal 5: Hypersonic flight
⇒*Rapid response and global reach*
- Demonstrate scramjets operable to Mach 10 on hydrocarbon fuel and to Mach 14 on hydrogen fuel

Figure 2. Relationship between Strike/Persistent Engagement R&D Activities and NS&HD Goals

Fixed-wing aircraft technologies pursued under the Strike/Persistent Engagement capability area include a futuristic hunter/killer concept that could execute all aspects of the kill chain with substantial sensor and weapon capabilities, with demonstration of key technologies in the mid term. The platform will require the ability to rapidly shift between ISR and target acquisition and attack roles, including the aggressive prosecution of multiple time-sensitive targets. To be most effective in theater, the system must retain the substantial loiter capability of current systems but also possess the ability to react quickly at high subsonic speeds. This capability will require research and technology consistent with Goal 1 to develop innovative aerodynamic and structural concepts for more efficient airframes. The system must also be able to handle diverse payloads including a variety of weapons, modular payloads such as additional sensor packages, and additional fuel.

The Adaptive Versatile Engine Technology (ADVENT) product will develop and demonstrate variable-cycle propulsion technologies, including inlet, engine, exhaust nozzle, and integrated thermal management systems that enable optimized propulsion system performance over a broad range of altitudes and flight velocities. A breakthrough ADVENT technology is a separate, third fan stream that can be modulated in terms of both airflow and pressure ratio. When combined with a variable-flow/variable-pressure-ratio secondary stream and a number of other enabling component technologies, this enables efficient operation over a large flight envelope. A key technical challenge with ADVENT is complex fluid and structural dynamics associated with the third stream and with the wide variation in operating conditions. Aligned with Goal 3, ADVENT is projected to enable a reduction in gas turbine specific fuel consumption of up to 25%, providing substantial payoffs in terms of mission radius and loiter for strike aircraft. Component technology demonstrations are planned in the near term, with a full engine demonstration in the mid term. Future plans will combine variable-cycle technology with improvements in thermodynamic efficiency to provide even greater gains in fuel efficiency.

The ability to generate power and control thermal loads on future strike aircraft is a key enabling technology as identified in Goal 4. One product in this area is Integrated Vehicle Engine Technology (INVENT). INVENT efforts are directed toward developing robust electrical power systems, high-performance electric actuation systems, and adaptive power and thermal management systems, all culminating in integrated modeling and hardware-in-the-loop demonstrations. Benefits will include decreased time to target and increased sortie rate or loiter time for long range strike applications; improved cooling for avionics, sensors, and other electronics, and increased range for global mobility. In the near term, silicon carbide power modules that are immune to electromagnetic and radio-frequency effects and with 2× increased operating temperatures will be tested. Demonstrations in that same time frame of wire insulation, permanent-magnet materials, engine controls, motor drives, and heat exchangers are also planned, with a mid-term objective to achieve a 5× increase in thermal transport and heat flux for power electronics. Successful demonstration of these technologies will enable development and demonstration of a complete, integrated thermal-management subsystem.

High-speed and hypersonic flight capabilities highlighted in Goal 5 offer great promise for Strike and Persistent Engagement. This requires R&D in both airframe and propulsion technology. Key airframe technologies include high lift-to-drag planforms; thermal management systems; high-temperature materials for engine and structural applications; structural design for high-Mach vehicles; and guidance, navigation, and control laws that are appropriate for this speed regime. These technologies are being investigated in flight test and flight demonstration programs such as the Falcon Hypersonic Technology Vehicle (HTV-2). Additional efforts are investigating supersonic combustion ramjet (scramjet) propulsion technologies. The X-51A Scramjet Engine Demonstration will flight test an actively cooled hydrocarbon fueled scramjet engine to at least Mach 6 and demonstrate flight times on the order of 5 minutes. After completion of the X-51A, further research will look to make the scramjet technology base more robust by expanding the operating envelope of scramjets from Mach 3.5 to 8 and possibly 10 for hydrocarbon fuels and up to Mach 14 for hydrogen fuel. The project will also begin design of larger scale engine concepts that will have 10 times to 100 times the airflow of the X-51A and include multi-cycle durability for reusable systems. In addition to these efforts, research in turbine-based combined-cycle propulsion is planned under several programs to enable high-Mach systems that can potentially take off and land using conventional runways.

In addition to the specific efforts identified here, there is a range of planned and ongoing R&D to address a spectrum of technology needs for Strike and Persistent Engagement. These R&D activities include advanced flight controls; efficient, compact propulsion systems for strike UAS and missiles; and high speed turbine based propulsion systems for high-speed missiles or as the basis for turbine-based combined-cycle engines. In addition, other technologies for higher efficiency or higher speed to expand the flight envelope for strike missions are being pursued. These specific R&D activities are in turn being supported by a strong foundation of ongoing research to continually improve understanding of flow phenomena, structural dynamics and aeroelasticity, controls, and thermodynamics in these flight regimes.

Air Superiority/Protection

A number of key technologies are required to prevent or mitigate an adversary's effect on joint forces and the populations that joint forces protect, ensuring freedom of maneuver. Aircraft power and rotorcraft survivability are important technologies to advance Air Superiority/Protection capabilities. Figure 3 shows a mapping of the relationship between technologies and the national security and homeland defense aeronautics R&D goals.

Satisfying key power and thermal requirements as described by Goal 4 is critical to enabling smaller, lighter aircraft to perform the Air Superiority/Protection mission. Directed energy weapons (DEW) technologies, enabled by megawatt (MW)-class power technologies, will allow scalable, nonlethal, high-power microwave airborne active-denial systems

Air Superiority / Protection and National Security Goals

Near-Term (0-5 years)

Goal 2: Improved rotorcraft performance and mission capability

⇒*Survivability and capability of rotorcraft*

- Rotorcraft survivability – Develop integrated threat warning and countermeasures
- Helicopter quieting – Develop analytical tools and component technologies for advanced, low-noise rotor concepts

Goal 4: Increased power and thermal management capacity

⇒*Mission capability and flexibility, directed energy capabilities*

- MW-class power – Demonstrate 4X increase in generator power density for DEW

Mid-Term (5–10 years)

Goal 2: Improved rotorcraft performance and mission capability

⇒*Survivability and capability of rotorcraft*

- Rotorcraft survivability – Test integrated threat warning systems
- Helicopter quieting – Flight test tactically significant acoustic signature reduction

Goal 4: Increased power and thermal management capacity

⇒*Mission capability and flexibility, directed energy capabilities*

- Integrated thermal/energy management systems – Demonstrate high efficiency fuel pump with 65% reduced heat

Far-Term (>10 years)

Goal 2: Improved rotorcraft performance and mission capability

⇒*Survivability and capability of rotorcraft*

- Demonstrate 50% reduction in acoustic perception range

Goal 4: Increased power and thermal management capacity

⇒*Mission capability and flexibility, directed energy capabilities*

- Demonstrate 10X increase in thermal transport and heat flux for DEW
- Demonstrate 50% weight and volume reduction for power and thermal management systems

Figure 3. Relationship between Air Superiority/Protection R&D Activities and NS&HD Goals

that have negligible casualties or low collateral damage. This power class will also offer potential for high-energy lasers for offensive and defensive counter-air operations and even conceptual future strike applications. Technology efforts are planned to deliver MW-class superconducting power generation; lightweight power distribution and conditioning; high-rate, high-flux thermal energy storage; and high-density energy storage systems that can operate in a dynamic environment. These technologies are projected to increase generator power density by 4× in the near term, with long-term plans to improve power and thermal management system weight and volume by 50% while increasing thermal transport and heat flux by up to 10× for advanced sensors and electronics and for future DEW.

Development of technologies that reduce system waste heat, increase cooling and power capacity, and provide for efficient system design and control is critical. Current projects include research in integrated thermal/energy management systems focusing on developing a suite of affordable, reliable, and adaptable component and subsystem technologies that aim to satisfy the thermal and power requirements of propulsion systems while minimizing penalties to the vehicle. One key challenge is the relatively low efficiency of fuel pumps, which currently add significantly to system waste heat. Research efforts plan to address this challenge by developing a high-efficiency fuel pump to reduce waste heat generated by 65%.

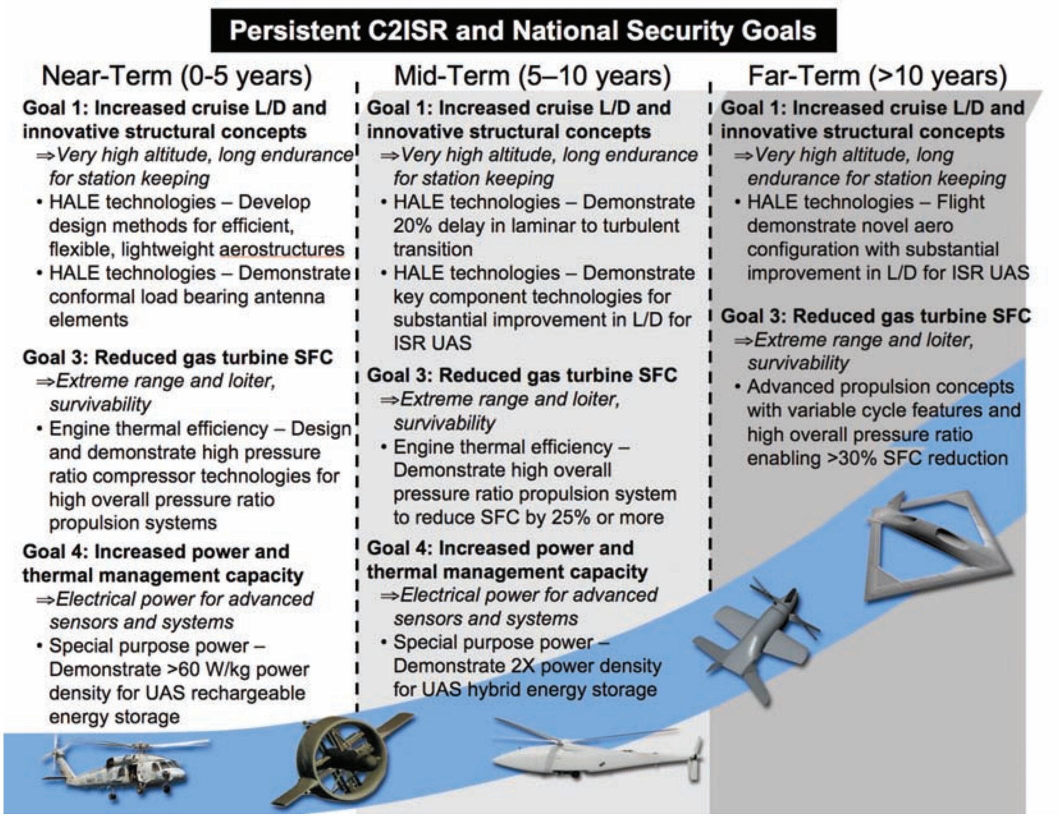
Rotorcraft survivability is an important aspect of Goal 2. For rotorcraft, the integration of crewed and uncrewed systems offers potential improvements in survivability, force application, and force protection. Utilizing the concept of distributed survivability, research efforts will concentrate on developing a fully integrated team-based aircraft self-protection suite for defeating current Man-Portable Air Defense System (MANPADS) threats, small arms and rocket-propelled grenades, antitank guided missiles, and radar threats. Distributed survivability involves a team of aircraft sharing detection and countering information and effects. Planned efforts include design of an integrated, multifunction threat warning and countermeasures suite in the near term, with flight demonstration in the mid term.

In addition to threat warning and countermeasures, studies and analyses of military helicopter operations have shown that their survivability and lethality can be increased by reducing their acoustic signature. Research aimed at helicopter quieting is developing new design tools that will enable the creation of rotor systems that can dramatically reduce the acoustic signature of a helicopter without significantly compromising flight performance. This effort will leverage recent advances in computational fluid dynamics to develop physics-based predictive design tools to explore the potential of emerging rotor noise reduction technologies. In the near term, the effort will investigate multiple advanced rotor concepts for application to fielded military rotorcraft for a significant reduction in low-frequency, in-plane signatures. The most promising concepts will be taken to test, culminating in full-scale flight experiments of advanced rotors in the mid and far terms.

In addition to these efforts, the ADVENT product described previously is developing variable-cycle technologies enabling propulsion system performance over a broad range of altitudes and flight velocities. For Air Superiority/Protection, ADVENT could provide additional benefits through enhanced aircraft range and loiter capability. Concurrent with ADVENT, the INVENT product will deliver critical power and thermal management for Air Superiority/Protection capabilities. INVENT technologies are projected to transition to the F-22, F-35, and future aircraft.

Persistent C2ISR

A number of key technologies, including efficient high-altitude configurations, engines optimized for high altitude, and increased aircraft power generation, are required to enable aircraft to remain on station and provide on-board aircraft power to sensors and electronics packages that allow the warfighter to continuously see and understand the battlefield



Persistent C2ISR and National Security Goals

Near-Term (0-5 years)

Goal 1: Increased cruise L/D and innovative structural concepts

⇒*Very high altitude, long endurance for station keeping*

- HALE technologies – Develop design methods for efficient, flexible, lightweight aerostructures
- HALE technologies – Demonstrate conformal load bearing antenna elements

Goal 3: Reduced gas turbine SFC

⇒*Extreme range and loiter, survivability*

- Engine thermal efficiency – Design and demonstrate high pressure ratio compressor technologies for high overall pressure ratio propulsion systems

Goal 4: Increased power and thermal management capacity

⇒*Electrical power for advanced sensors and systems*

- Special purpose power – Demonstrate >60 W/kg power density for UAS rechargeable energy storage

Mid-Term (5–10 years)

Goal 1: Increased cruise L/D and innovative structural concepts

⇒*Very high altitude, long endurance for station keeping*

- HALE technologies – Demonstrate 20% delay in laminar to turbulent transition
- HALE technologies – Demonstrate key component technologies for substantial improvement in L/D for ISR UAS

Goal 3: Reduced gas turbine SFC

⇒*Extreme range and loiter, survivability*

- Engine thermal efficiency – Demonstrate high overall pressure ratio propulsion system to reduce SFC by 25% or more

Goal 4: Increased power and thermal management capacity

⇒*Electrical power for advanced sensors and systems*

- Special purpose power – Demonstrate 2X power density for UAS hybrid energy storage

Far-Term (>10 years)

Goal 1: Increased cruise L/D and innovative structural concepts

⇒*Very high altitude, long endurance for station keeping*

- HALE technologies – Flight demonstrate novel aero configuration with substantial improvement in L/D for ISR UAS

Goal 3: Reduced gas turbine SFC

⇒*Extreme range and loiter, survivability*

- Advanced propulsion concepts with variable cycle features and high overall pressure ratio enabling >30% SFC reduction

Figure 4. Relationship between Persistent C2ISR R&D Activities and NS&HD Goals

and seamlessly communicate; make informed, timely decisions; and synchronize joint actions and efforts. Figure 4 is a mapping of the relationship between key technologies and the national security and homeland defense aeronautics R&D goals.

Persistent high-altitude, long-endurance (HALE) ISR capability blends a wide spectrum of emerging technologies into potential systems configured and optimized for sustained presence and advanced sensing capabilities. These will enable continuous and rapid reaction in current and evolving military operations. Maximizing aerodynamic efficiency and minimizing empty weight as described in Goal 1 are keys to enabling long loiter times and/or long ranges. HALE technologies being investigated include actively controlled wings, laminar flow control, and structurally integrated sensors and electronics. Research in multidisciplinary analysis and design of high-altitude aircraft configurations that include all these advanced technologies is needed to credibly assess performance and identify key trades in aircraft system design. Current investment strategies are striving toward flight testing of the technologies that support this capability in the mid to far term.

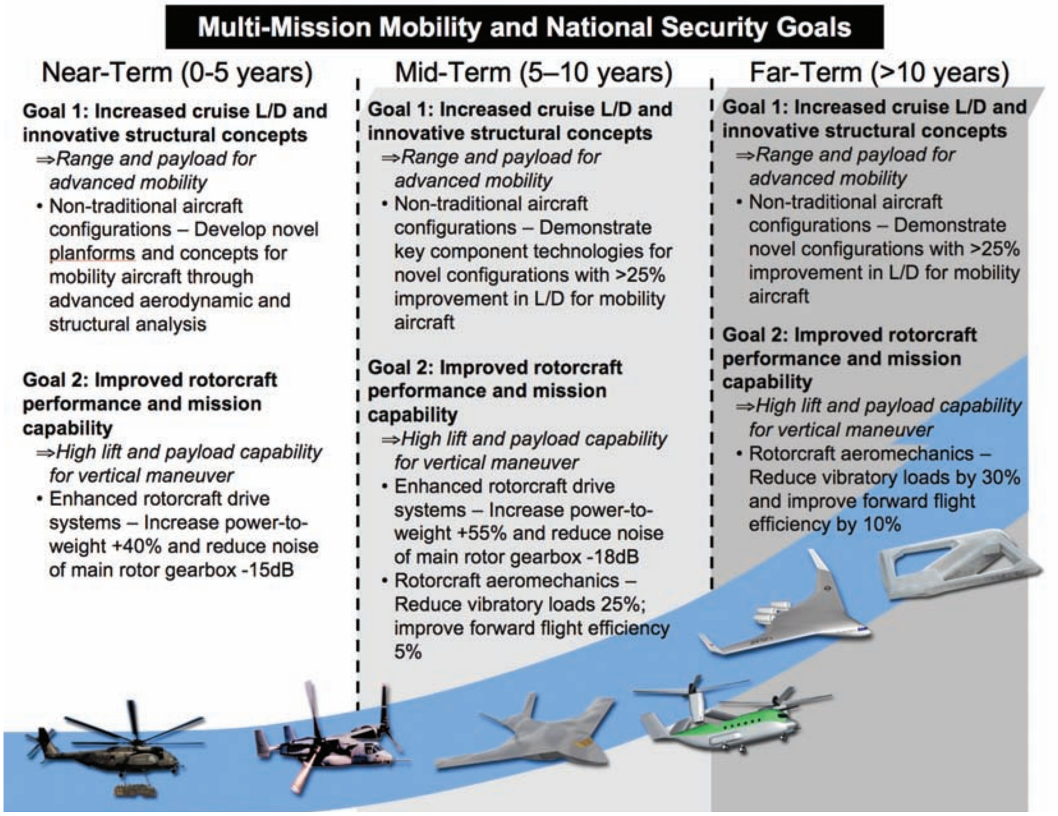
Research is underway to develop technologies enabling fuel-efficient, subsonic propulsion for high-altitude, long-loiter aircraft. Consistent with Goal 3, these technologies will enable reductions in engine specific fuel consumption of up to 25%. This research focuses on increasing the thermal efficiency of the engine by increasing the overall pressure ratio of the engine cycle. Advanced technologies include efficient turbo-machinery for high-altitude flight, a high-pressure-ratio fuel-efficient core, integrated propulsion and secondary power generation, efficient inlet and exhaust systems, a distortion-tolerant high-bypass fan, integrated thermal management, and high-temperature materials. Development of advanced high-pressure compressor technology is underway in the near term, with plans for full engine demonstrations in the mid term. Long-term plans will combine this with variable-cycle engine technology for even greater improvements in engine efficiency.

Small UAS provide important opportunities and capabilities for Persistent C2ISR. A key issue for very small UAS is compact power management and energy storage. Special-purpose power R&D is focused on developing 10 W to 2.5 kW class electrical power generation, hybrid energy storage, and power management components and systems as described in Goal 4 to enable Persistent C2ISR, as well as Strike/Persistent Engagement and Agile Combat Support/Enterprise and Platform Enabling capabilities. Small, lightweight power technologies are especially applicable to, and directly enable further capability for, battlefield air and ground operations and persistent surveillance for hand-launched, small UAS or air-dropped, long-endurance munition UAS missions. The high-power, high-density hybrid energy storage systems being developed through this research will reduce overall aircraft weight and volume, thereby significantly increasing aircraft endurance and loiter time and reducing the transportation burden on the warfighter. In addition to research into power and energy technologies, there is ongoing research in the fundamental understanding of low Reynolds number flight. Research is ongoing in computational tools, fluid-structure interaction, and flapping flight as it applies to small UAS.

In addition to these efforts, research into novel aircraft planforms; compact, efficient propulsion systems; advanced sensors; and automated controls is ongoing. Also, with power requirements for onboard sensors, technologies developed under MW-class power technology efforts could provide improved generator efficiency, increased on-board power available, and increased power and energy density leading to smaller, lighter power systems. This reduction in power subsystem weight is directly beneficial to reducing both aircraft size and increasing aircraft range and endurance.

Multi-Mission Mobility

The ability to move materiel and personnel responsively and efficiently is critical to meeting future joint aerial maneuver and lift requirements. Although many of the technologies described previously also benefit Multi-Mission Mobility, other technologies are uniquely required to enable this critical capability. Figure 5 is a mapping of the relationship between key technologies and the national security and homeland defense aeronautics R&D goals.



Multi-Mission Mobility and National Security Goals

Near-Term (0-5 years)

Goal 1: Increased cruise L/D and innovative structural concepts

⇒Range and payload for advanced mobility

- Non-traditional aircraft configurations – Develop novel planforms and concepts for mobility aircraft through advanced aerodynamic and structural analysis

Goal 2: Improved rotorcraft performance and mission capability

⇒High lift and payload capability for vertical maneuver

- Enhanced rotorcraft drive systems – Increase power-to-weight +40% and reduce noise of main rotor gearbox -15dB

Mid-Term (5–10 years)

Goal 1: Increased cruise L/D and innovative structural concepts

⇒Range and payload for advanced mobility

- Non-traditional aircraft configurations – Demonstrate key component technologies for novel configurations with >25% improvement in L/D for mobility aircraft

Goal 2: Improved rotorcraft performance and mission capability

⇒High lift and payload capability for vertical maneuver

- Enhanced rotorcraft drive systems – Increase power-to-weight +55% and reduce noise of main rotor gearbox -18dB
- Rotorcraft aeromechanics – Reduce vibratory loads 25%; improve forward flight efficiency 5%

Far-Term (>10 years)

Goal 1: Increased cruise L/D and innovative structural concepts

⇒Range and payload for advanced mobility

- Non-traditional aircraft configurations – Demonstrate novel configurations with >25% improvement in L/D for mobility aircraft

Goal 2: Improved rotorcraft performance and mission capability

⇒High lift and payload capability for vertical maneuver

- Rotorcraft aeromechanics – Reduce vibratory loads by 30% and improve forward flight efficiency by 10%

Figure 5. Relationship between Multi-Mission Mobility R&D Activities and NS&HD Goals

Research in nontraditional aircraft configurations looks to develop unique forms characterized by highly efficient aerodynamics and lightweight structures, consistent with the objectives of Goal 1. Significant improvements in aircraft lift to drag could be realized with unconventional planforms such as hybrid-wing or blended-wing bodies. In addition, these configurations can leverage ongoing work in emerging structural concepts to reduce aircraft weight and increase regions of laminar flow. With the addition of novel propulsion integration concepts such as the use of boundary layer ingesting inlets and active flow control, potential capability improvements include significantly improved range and endurance, as well as increased payload and fuel offload for tanker applications. Key technology challenges include the development of large, efficient, noncircular pressure vessels for crewed aircraft; fabrication and reliability of large unitized structures; large, smooth surface contours for improved aerodynamics; performance of large, active aeroelastic structures; advanced flight-control systems; and efficient propulsion integration.

For rotary-wing aircraft, the drive system that couples the engines to the rotors encompasses a large fraction of the system empty weight and requires significant maintenance. To reduce this system's weight and associated support costs, research efforts for enhanced rotorcraft drive system capability look to provide a significant increase in power-to-weight ratio, a reduction in both production and operating and support costs, and a reduction in noise for the drive systems of both crewed and uncrewed rotorcraft as described in Goal 2. These technologies would enable greater payload, range, and speed for current rotary-wing platforms as well as future systems. Key technologies are helical face gears and composite gearbox housings. Component design and fabrication are planned in the near term, with testing of advanced drive train technology under realistic loading conditions planned in the mid term. Additional research in variable-speed drive systems, oil-free engine technology, and engine technologies enabling wide operability and increased power could provide further benefits for future rotorcraft.

Technology development efforts in rotorcraft aeromechanics will mature advanced control methods for improving rotorcraft performance in a heavy vibration environment, another key element of Goal 2. Technologies include high-lift rotor systems to provide improved aerodynamic performance while enhancing damage tolerance, advanced main-rotor hub concepts compatible with on-blade rotor control systems, and lightweight rotor control technology intended to improve aerodynamic efficiencies and maximize air vehicle performance. Results of this technology development will provide current and future rotorcraft with greater range and endurance characteristics and keep armed rotorcraft on station or in the fight longer, which also benefits the Strike/Persistent Engagement capability area. Design of an integrated rotor control system is planned in the near term with wind tunnel testing and flight tests in the mid and far terms.

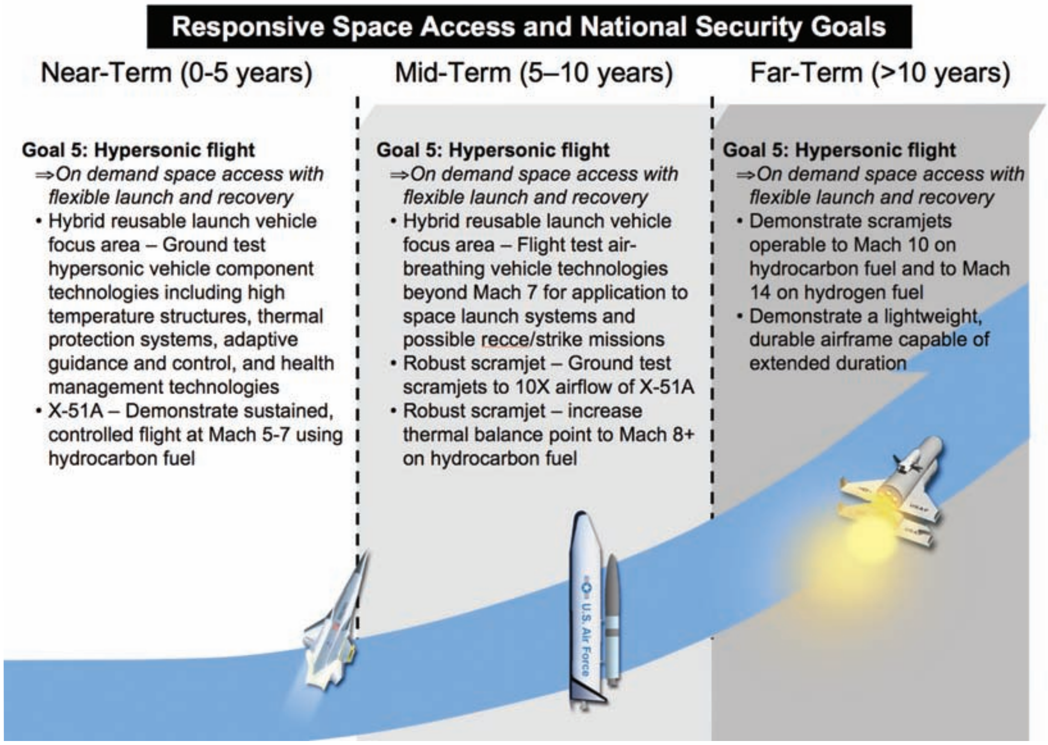
Other R&D efforts are exploring vertical and STOL capabilities for Multi-Mission Mobility. These include a cruise-efficient takeoff and landing concept to enable STOL capability for aircraft with cruise efficiency suitable for transoceanic routes, variable- and optimum-speed rotors to maximize flight efficiency for rotorcraft over a broader flight envelope, and a heliplane concept to combine aspects of vertical lift with horizontal cruise. Technical challenges include rotors and propulsion systems that are adaptable to different flight conditions, variable-speed drive systems, and aeroelastic phenomena in flight mode transition.

An important mobility application for national security is aerial refueling. With increased use of UAS, the ability to refuel these aircraft becomes a key mobility issue. Research in automated aerial refueling technology is focused on providing aerial refueling technology for integration into future UAS. Major elements of this research effort include studies to establish operational requirements and conceptual designs, wind tunnel tests and analysis aimed at controllability issues for UAS in a tanker wake, positioning system development, simulations, and flight tests. "Hands-off" station-keeping and formation maneuvering with a KC-135 and crewed surrogate have been demonstrated for both probe-and-drogue systems and boom-and-receptacle systems. Continued technology demonstration is planned in the near term in pursuit of transition into operational UAS.

Responsive Space Access

The capability to access space on demand is important for future national defense and security. For purposes of this plan, this capability area is primarily associated with maneuvering hypersonic flight as described in Goal 5. A number of key technologies in propulsion; thermal protection systems; guidance, navigation, and control; materials; structures; and health management are required to provide quick access to and return from space with flexibility in launch and recovery. A mapping of the relationship between key technologies and the national security and homeland defense aeronautics R&D goals is shown in Figure 6.

Research activities in Responsive Space Access include a hybrid reusable launch vehicle focus area, with a long-term vision to mature technologies enabling a fully reusable two-stage-to-orbit launch vehicle. Current efforts involve integrating ongoing work in structures, thermal protection systems, adaptive guidance and control, health management, and other subsystems into a set of coordinated ground experiments in the near term. Follow-on activities will focus on flight testing technologies for a maneuverable vehicle capable of flight velocities up to Mach 7 in the mid term, with long-term plans for testing a lightweight, durable airframe capable of extended duration at hypersonic speeds.



Responsive Space Access and National Security Goals

Near-Term (0-5 years)

Goal 5: Hypersonic flight

⇒*On demand space access with flexible launch and recovery*

- Hybrid reusable launch vehicle focus area – Ground test hypersonic vehicle component technologies including high temperature structures, thermal protection systems, adaptive guidance and control, and health management technologies
- X-51A – Demonstrate sustained, controlled flight at Mach 5-7 using hydrocarbon fuel

Mid-Term (5–10 years)

Goal 5: Hypersonic flight

⇒*On demand space access with flexible launch and recovery*

- Hybrid reusable launch vehicle focus area – Flight test air-breathing vehicle technologies beyond Mach 7 for application to space launch systems and possible recce/strike missions
- Robust scramjet – Ground test scramjets to 10X airflow of X-51A
- Robust scramjet – increase thermal balance point to Mach 8+ on hydrocarbon fuel

Far-Term (>10 years)

Goal 5: Hypersonic flight

⇒*On demand space access with flexible launch and recovery*

- Demonstrate scramjets operable to Mach 10 on hydrocarbon fuel and to Mach 14 on hydrogen fuel
- Demonstrate a lightweight, durable airframe capable of extended duration

Figure 6. Relationship between Responsive Space Access R&D Activities and NS&HD Goals

Other efforts under Responsive Space Access strongly leverage research being performed under the Strike/Persistent Engagement capability area. The Falcon program is maturing technologies, such as high-temperature materials for engine and structural applications; thermal protection systems; and guidance, navigation, and control, for hypersonic vehicles. The X-51A and other scramjet research efforts are advancing the fundamental knowledge base for scramjet propulsion systems. Other efforts are advancing high-Mach turbine engine technology and enabling turbine-based combined-cycle propulsion systems. In addition, rocket-based combined-cycle propulsion technology holds considerable promise for air-breathing access to space.

The underpinnings of these concepts are found in foundational research programs. In the area of materials and structures, a series of research efforts are focused on developing multifunctional materials with significantly enhanced capabilities such as higher temperatures, self-sensing and self-healing, and the possibility to manufacture sufficiently large pieces that could lead to the production of full-scale vehicles. Modeling and simulation developments are needed to ensure that both high-fidelity multidisciplinary and engineering-level tools can be used to perform trade studies on propulsion system configurations to account for integration effects on installed performance, operability, durability, and weight, along with uncertainties. Finally, these advanced modeling capabilities must be extended to a full-scale hypersonic vehicle to ensure accurate assessment of the alternatives that will materialize for Responsive Space Access.

Agile Combat Support/Enterprise and Platform Enablers

Within the national security and homeland defense capability-based planning construct, there are a number of technology developments underway that are cross-cutting and focus on a mix of more broadly based challenges that are pervasive across several of the capability domains that have been described previously. These technologies generally have multiple applications and are important for enabling full-spectrum system capabilities through design and analysis; modeling and simulation tools, techniques, and processes; and the application, insertion, and integration of technology. While numerous technology efforts are addressing a range of needs, three areas of particular interest are aerospace fuels, cooperative airspace operations, and reducing life-cycle costs.

Aerospace Fuels

Dramatic fuel price increases and price volatility create planning and budget concerns for executive departments and agencies. Moreover, fuel represents the single largest commodity delivered to theater for military missions and therefore comprises an important logistics issue. A wide variety of fuels and fuel types for various applications, each with its own storage and delivery systems, exacerbate an already significant logistics effort. Research efforts seek to reduce the number of different fuels on the battlefield, ideally through development of a single, environmentally friendly fuel with composition and properties sufficient to serve the needs of a multi-vehicle, multi-mission battle-space environment. A significant outcome of this work is to develop a knowledge base to streamline fuel certification and introduction for military use, beginning with Fischer-Tropsch (F-T) fuels. This fuel certification project is an important part of the greater effort in alternative aviation fuels described in the Energy and Environment sections of the Plan and this Technical Appendix.

Cooperative Airspace

Integrating more aircraft into the airspace requires new methods to handle aircraft de-confliction, especially with the growing use of UAS. A number of initiatives are directed toward UAS and their integration with current and future crewed systems. One of the more pervasive challenges is situational awareness to maintain de-confliction, avoid collision, and allow both crewed and uncrewed platforms to operate cooperatively in theater. The development of sense-and-avoid technologies for use by UAS to detect other aircraft in the vicinity of the host and maneuver to avoid potential collisions is critical for integrated uncrewed operations, as well as joint crewed and uncrewed operations. Additional technologies that might enable the integration of UAS in theater and into the national airspace are intelligent agents that allow systems to adapt to their environment; open system architectures; planning tools that allow civil and military planners to incorporate and coordinate operations of crewed and uncrewed aircraft; and situational awareness improvements not only for aircraft, but also for air traffic controllers and operations planners. Moreover, key research areas not unique to aviation but essential for cooperative airspace operations of UAS include autonomous systems and human-machine interaction.

Life-Cycle Costs

Growth in the life-cycle costs of aviation systems, and particularly air platforms, is an important concern for national security and homeland defense. R&D to reduce development, production, and maintenance costs would provide benefits for sustaining current aviation systems, as well as developing new systems. One approach to reducing development costs is improved use of modeling and simulation to more quickly achieve desired system performance and reduce overall design time and costs. Areas of research include multidisciplinary analytical tools and design methods for materials that have multiple roles, such as electronic components that are also load-bearing structures; advanced materials with greater lifetime and fatigue resistance; fluid-structure interaction; the interaction of shear and vortex flows in turbo-machinery and within airframe cavities; and microfluidics for aerodynamic and thermal control. Significant gains may also be made to affect manufacturing and production costs of aircraft and aircraft components and subsystems. New analytical and design methods may allow concepts such as manufacturing for purpose and large, unitized structures to become possible on a production scale and in turn reduce expensive tooling, which accounts for some of the largest up-front costs in building an aircraft. Finally, with aircraft being in service much longer than before, the ability to maintain and ensure airworthiness is also vitally important. Improved modeling and simulation tools, linked with probabilistic design techniques and advanced usage tracking, data collection, and damage prognosis, allow improved inspection and maintenance procedures that could significantly reduce operating and sustainment costs across all aircraft components and types. These technologies enable key concepts such as integrated vehicle health management (IVHM) and condition-based maintenance, which can significantly reduce maintenance costs for aircraft systems.

Foundational Research

Foundational research supports national security and homeland defense aeronautics R&D by providing the knowledge and understanding critical to solving difficult technical problems with aircraft systems and the advanced concepts, tools, and future technologies to maintain and advance national security and homeland defense capabilities well into the future. The key to a successful foundational research program is long-term stability and focus, allowing researchers to take risks and innovate, while being allowed to fail.

Broad-based, sustained foundational research will continue to be needed to advance new ideas in propulsion; aerodynamics; materials and structures; guidance, navigation, and control; acoustics; mathematics; and computational science. This research is needed to further the state of the art in modeling and simulation as well as advanced concepts and design tools to enable future military and civil aircraft. For national security and homeland defense, additional areas of emphasis include the science of autonomy, which focuses on decision-making and control of single and multiple uncrewed autonomous vehicles; aerodynamics of very small, slowly moving air vehicles; and energy and power management, which involves research in energy and power conversion, high energy and pulse power architectures and control, energy storage, and alternative energy sources. These foundational research areas are well aligned with several of the fundamental technical challenges and goals in national security and homeland defense aeronautics R&D and provide important opportunities to advance national capabilities in these areas.

Advanced Component Development and Prototypes

Advanced component development and prototypes provide the final stages of research and technology demonstration prior to developing operational systems. These efforts are necessary to evaluate integrated technologies, representative implementations, or prototype systems in a high-fidelity and realistic operating environment. At this stage, efforts focus more on technology development than research, but there is still significant technology risk that requires a concerted effort to address, often leading to a prototype or similar level of demonstration. Successful technology demonstrations of this nature often result in the initiation of development programs for military weapons systems or other government applications.

An important program currently underway is the Joint Precision Approach and Landing System (JPALS), a joint effort among the military Services to define the future precision approach and landing system for the DOD from shipboard, fixed-base, tactical, and special operations environments under a wide range of meteorological conditions. JPALS will provide a precision landing capability where none currently exists; interoperability for naval aircraft landing at shore-based airfields, including those operated by other military Services; and interoperability for Navy, Marine Corps, and Army aircraft landing at civil airports, as well as for the Civil Reserve Air Fleet landing at DOD airfields.

Another important effort is the Long Range Strike Advanced Concept and Development program, which is focused on developing and demonstrating the technologies that will enable a next generation long range strike capability in support of Air Force concepts of operations. Currently, a wide variety of concept options are being considered for a long range strike air platform, but technology efforts are underway that will develop radiofrequency/electro-optical/infrared sensor technology for accurate target detection and identification, high-temperature and variable-cycle engine components, sensor/aperture integration technology, and advanced weapon integration technology.

A third program is the HTV, which supports future prompt global strike needs for a capability to strike globally, precisely, and rapidly. HTV-class vehicles could deliver kinetic effects against high-payoff, time-sensitive targets, regardless of anti-access threats in a single theater or multi-theater environment, when U.S. and Allied forces have limited or no regional military presence. Building on the Falcon program, the HTV program will evaluate integrated technologies in as realistic an operating environment as possible to assess performance. Using flight tests, the HTV program will mature operational requirements, study basing alternatives, and conduct effectiveness demonstrations and payload survivability assessments.

ANALYSIS OF OPPORTUNITIES WHERE ADDITIONAL R&D FOCUS MAY BE WARRANTED

The National Security and Homeland Defense aeronautics R&D goals and objectives were assessed in light of the activities described in this Technical Appendix to identify areas of opportunity for potential increased emphasis as well as potential areas of unnecessary redundancy. The methodology for this assessment considered the previously described four key issues:

- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the near term;
- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the mid to far term;

- The level of coordination among executive departments and agencies; and
- The level of redundancy of efforts among executive departments and agencies.

Each of these four areas was given a broad assessment of green, yellow, or red based on this review. A green assessment denotes that R&D activities planned or ongoing are sufficient to achieve the objectives in the time frame indicated, that there is strong coordination among executive departments and agencies, and that there is no unnecessary redundancy. A yellow assessment indicates that R&D activities should provide significant progress toward the objectives but there is some risk due to fiscal or other constraints that merits continued attention, that coordination is taking place but could be improved, or that there does not appear to be unnecessary redundancy but additional coordination may be warranted. A red assessment highlights an area where additional emphasis or improved coordination among executive departments and agencies may be warranted to achieve the objective. The overall results of this analysis for National Security and Homeland Defense are shown in Table 3 at the end of this section.

As shown in Table 3, no major issues were identified with the sufficiency of planned and ongoing efforts for meeting national security and homeland defense aeronautics R&D objectives in the near term. Efforts in rotorcraft performance and survivability, variable-cycle propulsion, and power and energy management were particularly strong. In other areas, significant progress toward the objectives is expected, but continued attention will be needed to balance technical risk in these areas against available resources. In the mid to far term, three major areas of concern were identified—rotorcraft aeromechanics and performance, advanced gas turbine propulsion, and hypersonic airframe technology. Each of these areas is addressed in more detail under the associated goal below.

Goal 1 – Demonstrate increased cruise lift-to-drag and innovative airframe structural concepts for highly efficient high-altitude flight and for mobility aircraft

Key fixed-wing aircraft technologies are focused on improving the flight efficiency of subsonic aircraft, both for uncrewed reconnaissance applications and crewed mobility applications. Research efforts are expected to produce significant progress toward these objectives. However, this area is challenged by a need to ground test many technologies at a large scale to produce realistic results. Moreover, some conditions require flight testing to fully characterize, which can be very costly. Continued attention will be needed to balance the technical risks associated with large scale ground tests or flight tests with available resources. Interagency coordination in this area is sufficient, though improvements are possible. However, no unnecessary redundancy was noted among research activities in this area.

Goal 2 – Develop improved lift, range, and mission capability for rotorcraft

The objectives associated with this goal focus on both aircraft performance and aeromechanics as well as aircraft survivability. As shown in Table 3, ongoing or planned research is expected to achieve the objectives in both these categories in the near term, and in general there is strong coordination among executive departments and agencies and as such there is no unnecessary redundancy. Research efforts in threat warning and countermeasures as well as rotorcraft noise reduction are not as strongly coordinated among departments and agencies, but that is primarily the result of the uniqueness of these objectives to military aircraft. It should be noted that the noise reduction research here is somewhat different from that described in the Energy and Environment section with regard to civil aviation because it focuses on acoustic perceptibility from an aircraft survivability standpoint.

Table 3 shows an area of concern in the far term for rotorcraft aeromechanics and performance objectives. While R&D efforts are well positioned to achieve the near-term objectives in these areas, these objectives are primarily focused on expanding current rotorcraft capabilities. However, the farther term must address enabling different types of rotorcraft capability, such as heavy lift or high speed, if these capabilities are to be realized. At present, there is not a consensus among federal stakeholders on a vision for future rotorcraft capability, and thus there is also not a consensus on the direction of R&D for future rotorcraft. This is an issue for national security and homeland defense, but also influences and is influenced by the civil sector.

A number of efforts are beginning to address a long-term vision and strategy for rotorcraft R&D. Until these efforts mature, it is unclear whether the objectives established for the mid to far term are adequate to address potential future rotorcraft capabilities. Moreover, it is unclear whether the current R&D program is sufficient to address these needs. As such, the rotorcraft aeromechanics and performance objectives will be revisited in the biennial review of the Plan. A key aspect of the review process will be strong coordination among federal and non-federal stakeholders to reach a vision for future rotorcraft capability.

Goal 3 – Demonstrate reduced gas turbine specific fuel consumption

The objectives associated with this goal recognize two paths to improved propulsion efficiency: increased thermal efficiency in the Brayton cycle through increasing the overall pressure ratio of the propulsion system and optimizing the performance of a propulsion system across the flight envelope through variable-cycle technology. Research efforts in variable-cycle technology are strong and well positioned to achieve the objectives in the near and mid terms. Interagency coordination is somewhat limited due to a strong focus on military applications, but no unnecessary duplication was identified. Research in improved thermal efficiency is expected to produce significant progress in the near term through component-level demonstration of key technologies. Research efforts are generally coordinated, and no unnecessary redundancy was identified. Because of the potential for significant applications in the civil commercial sector, it will be important that interagency coordination receive continued attention to ensure that redundancy does not occur in the future.

An area of concern in the far term is shown in Table 3 for this goal. In this time frame, variable-cycle technologies and technologies to improve engine thermal efficiency are expected to be combined to produce dramatic improvements in propulsion system specific fuel consumption. Either path for improving propulsion efficiency requires significant resources to realize the objectives due to the technical risk associated with these high-payoff technology advances. Consequently, it will be challenging to sustain the resources needed to develop both technical paths in parallel and bring them to fruition together. One important approach is to reduce technical risk in these approaches through the use of higher temperature materials in the high-pressure compressor, combustor, and turbine. However, investment in these materials lags the advancement of the associated component technologies, making alternative approaches such as advanced cooling and thermal management necessary. This issue also has implications for thermal management that should be considered.

Goal 4 – Demonstrate increased power generation and thermal management capacity for aircraft

Power and thermal management are growing concerns as aircraft performance continues to increase along with power and thermal loads for advanced electronics and propulsion. In addition, power solutions are needed for very small UAS. In the near term, ongoing or planned research is generally expected to achieve the objectives for this goal. Interagency coordination is sound, particularly in the area of power for very small applications, and no redundancy was noted. In the far term, significant progress is expected, but there is some risk because of the dynamic growth of power and thermal management capacity needs and the relative immaturity of research in this area, especially thermal management. As research progresses, new knowledge could result in new areas for exploration, which should be reflected in the far-term objectives and associated research efforts.

Goal 5 – Demonstrate sustained, controlled, hypersonic flight

Research in hypersonics has advanced significantly in recent years and is expected to continue to advance. However, this area will continue to be challenged by the technical risks of flight in the extreme hypersonic environment and the subsequent costs associated with experimentation. In particular, many experiments require an environment that cannot be simulated in ground tests and thus require expensive flight tests to perform. This area will need continued attention to balance these technical risks against available resources. However, interagency coordination in this area is excellent, and as a consequence, no unnecessary redundancy was identified.

While progress has been noted in hypersonic research, much of the focus has been on propulsion technology, an exigent issue in hypersonic flight. However, research in high-temperature materials and thermal protection systems for hypersonic vehicles has lagged behind propulsion technology. In the near term, vehicles are projected to have relatively short flights. In the future, as flight durations are expected to increase, vehicle thermal protection will become more critical in permitting extended flight duration. In addition, flight velocities are expected to increase, resulting in higher operating temperatures. As such, additional emphasis is warranted for thermal protection systems and high-temperature structural materials suitable for the hypersonic environment.

Additional Area of Concern—UAS

The National Security and Homeland Defense section of the Plan identifies a fundamental technical challenge associated with UAS integration in the airspace. This is a complex issue with R&D solutions required on many levels. There are the inherent safety needs of operating UAS in the NAS, and research efforts are needed both to enable UAS integration in the NAS as well as to understand safety implications and certification requirements. Another issue, however, is operation of multiple UAS, including very small platforms, in the tactical environment in a military theater of operations, and the potential integration of these aircraft into theater airspace with crewed platforms having diverse operational characteristics. Additionally, some future concepts will consider having multiple UAS operated by a single person. These and other issues make integration and de-confliction of UAS in airspace for national security and homeland defense challenging. At present, there is no goal associated with this challenge. However, as this area matures, it is likely that a goal and associated objectives will be developed to address this important need as part of the biennial review of the Plan.

SUMMARY

Overall, no major issues were identified with the sufficiency of planned and ongoing efforts for meeting national security and homeland defense aeronautics R&D objectives in the near term. Interagency coordination is generally strong and effective, and no areas of unnecessary redundancy were identified. Three areas of concern were identified in the far term. It is expected that these areas will be addressed through the organic planning processes of appropriate executive departments and agencies. However, continued improvement of interagency coordination in these areas will help to inform and improve these processes and lead to more effective planning and execution of the resulting research activities.

Table 3. National Security and Homeland Defense Opportunities Analysis

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)	Near Term Objectives	Interagency Coordination	Redundancy	Mid and Far Term Objectives
Goal 1 Demonstrate increased cruise lift-to-drag and innovative airframe structural concepts for highly efficient high-altitude flight and for mobility aircraft	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	Y	Y	Y	Y
	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	Y	Y	Y	Y
Goal 2 Develop improved lift, range, and mission capability for rotorcraft	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)		G	G	G	R
		Reduce vibratory loads 25%; improve forward flight efficiency 5%	Reduce vibratory loads by 30% and improve forward flight efficiency by 10%	Y	G	G	R
	Develop integrated threat warning and countermeasures	Test integrated threat warning systems		G	Y	G	Y
	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	Y	Y	G	Y
Goal 3 Demonstrate reduced gas turbine specific fuel consumption	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	Y	Y	Y	R
	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		G	Y	G	G

Table 3. National Security and Homeland Defense Opportunities Analysis—continued

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)	Near Term Objectives	Interagency Coordination	Redundancy	Mid and Far Term Objectives
Goal 4 Demonstrate increased power generation and thermal management capacity for aircraft	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 DEW	G	Y	G	Y
	Demonstrate 4× increase in generator power density for DEW	Demonstrate high-efficiency fuel pump with 65% reduced heat	Demonstrate 50% weight and volume reduction for aircraft power and thermal management systems	Y	Y	G	Y
	Demonstrate >60 W/kg power density for UAS rechargeable energy storage	Demonstrate 2× power density for UAS hybrid energy storage		G	G	G	G
Goal 5 Demonstrate sustained, controlled, hypersonic flight	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	Y	G	G	Y
	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	Y	Y	G	R

AVIATION SAFETY IS PARAMOUNT

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

INTRODUCTION AND BACKGROUND

To fulfill the guiding principle that "Aviation safety is paramount," the goals for aviation safety R&D are to develop the technologies, tools, and methods required to:

- Improve aircraft, passenger, and crew safety for current and future aircraft; and
- Overcome safety technology barriers that would otherwise constrain full realization of the NextGen.

NextGen envisions a safer, more efficient and reliable air transportation system in 2025, freed from many of the constraints in the current system, that supports a wider range of operations and delivers a 2× to 3× overall increase in airspace system capacity. This transformation requires a shift from a rigid system based on established technology infrastructure to a system that is flexible and adaptable to the varied needs and capabilities of its users. This will require a prognostic approach to safety and a new safety culture that exploits and reduces risk through the use of predictive tools.

The current air transportation system is extremely safe, as evidenced by today's very low commercial accident rate. This high safety level must be maintained and improved into the future. Already today, aviation faces an increasingly demanding operational environment in which operators seek to stretch resources and in which air traffic must operate as efficiently and as safely possible. New aircraft are likely to be introduced to the system, including new GA, advanced rotorcraft, very light jets, and UAS. New business models, such as the incipient air taxi business and other services that take advantage of new vehicle capabilities, will further add to the density and complexity of operations in the most intensely used areas of the NAS. Even if air traffic grows more slowly than anticipated, projected demands on the aviation enterprise will stress current safety approaches and technologies and require significant improvements in safety management capabilities.

It is important to understand the safety impacts of these new vehicles and business models and increased density of operations and develop capabilities to mitigate resulting safety impacts. NextGen will require the introduction of new safety concepts, systems, technologies, and procedures to achieve acceptable levels of safety in this more complex and more demanding environment. Aggressive efforts to develop technological solutions for improving safety are imperative. These solutions will need to be developed and implemented systematically and strategically.

Safety is paramount to public confidence and a fundamental duty of the aviation enterprise. If safety cannot be assured, then increases in the density and diversity of aircraft operations to meet projected demand will not be permitted. Thus, the fundamental concern of aviation safety for the future is to continually improve aviation's historically low accident rate as more people fly, the number of aircraft and operations increase, and the diversity of aircraft increases. It cannot be overemphasized that it is essential to continually improve the aviation accident rate in order to prevent an increase in the actual number of aircraft accidents as volume increases.

STATE OF THE ART

The aviation industry provides by far the safest mode of transportation available in the United States. The average commercial fatal accident rate has declined to its lowest level—0.022 per 100,000 flight hours. This represents a 57% drop in aviation accidents over the past 10 years. The declining accident rate highlights the fact that improving safety is a core value throughout the entire aviation industry.

Vehicle Safety

Commercial aviation has achieved an impressive safety record. The primary contributor to fatalities worldwide over the past two decades—controlled flight into terrain—is no longer a major concern with U.S. airlines. Controlled flight into terrain mishaps were substantially reduced as a result of regulations and an industry-wide emphasis to implement enhanced ground-proximity warning systems and related operational procedures.

The second largest contributing factor is loss of control in flight. Established, rigorous methods currently exist for developing and verifying flight-control systems that maintain stable flight and that, in recent years, dramatically improve flight efficiency and enable new air traffic operations such as RNP procedures. However, these flight-control systems are based on detailed flight dynamics modeling, often supported by extensive testing in wind tunnels and flight, and by computational modeling, based on a large body of knowledge that is limited to the dynamic behavior of current aircraft configurations within the steady-flight conditions within the flight envelope.

Structural and component failures are contributing factors to 24% of on-board fatalities and are underlying factors in many of the 26% of the accidents caused by loss of control in flight. Aircraft structures in recent aircraft have largely been made from a common set of metallic materials, whose fundamental properties in terms of design strength have been well established. The aging of the current metallic (primarily aluminum) fleet of aircraft is well understood, due in part to the successful aging aircraft research programs in the FAA, the DOD, and NASA. At this time, new materials are starting to be applied whose long-term behavior is less understood. These include the application of composite materials to reduce weight; new metallic materials in the engine to allow for higher temperature, more fuel-efficient operations; and hybrid materials that seek to combine the benefits of both composite and metallic materials.

In addition, commercial airliners continue to have many unresolved maintenance issues that lead to safety problems. Nondestructive evaluation (NDE) methods exist and continue to be developed to better detect structural degradation in response to events (e.g., tail strikes or small "dings" during ground handling) and aging. However, these techniques can be sufficiently intrusive that they can also create problems. For example, maintenance on one component generally requires removing and reinstalling its inspection panels and tubing and wiring connectors and those of its neighbors, with commensurate opportunities for error (e.g., incorrect or incomplete reinstallation) or new damage (e.g., wire chafing).

Today, some sensors are built into aircraft to detect failures. However, these sensors are typically limited in number and capability, such as a few sensors located in an engine to monitor temperature, pressure, and revolution rate. Widespread use of such sensors is limited due to the intrusiveness of the sensors, the difficulty and cost to incorporate them into aircraft structures, the extreme conditions within which many sensors would operate (e.g., hot sections within engines), and their unproven reliability.

Aircraft electronic systems and avionics have become exceedingly complex because these systems control many functions in modern aircraft. For example, full authority digital engine controls (FADEC) systems control propulsion systems to improve fuel efficiency. Flight-management systems automatically control a vehicle's dynamic behavior and establish optimal flight trajectories. The software in a modern flight deck can run to millions of lines of code, and faults within complex avionics systems can be difficult to isolate and diagnose. As a result, verification and validation of new and innovative systems can be prohibitively expensive. Hence, new system development is typically limited to an incremental evolution from established hardware architectures and software systems rather than a transformational change in the system's capabilities.

Safe Operation of Vehicles

Operations within the NAS are designed to fit within a technology infrastructure and operating concepts whose fundamental structure was determined decades ago. Safeguards and redundancy are built into the system specifically to maintain safety. For example, route structures are designed to accommodate unexpected deviations or navigation variance by airplanes, and failures in one of the communication, navigation, or surveillance functions of an aircraft can be mitigated through special operating procedures relying on the two remaining functions. This robustness is vital given that anomalies (e.g., transponder failures, the need for an aircraft to have priority for medical or security reasons, or missed approaches) are part of normal operations. However, the NAS has effectively reached its capacity limit in several metropolitan areas and the resulting delays impact the performance of the entire NAS. Hence, meeting projected demands for air transportation growth demands transformative changes in air traffic operations whose safety cannot be extrapolated from models of the current system and whose inherent buffers and redundancy may need to be reduced. Systematic prediction of safety levels and identification of potential hazards is beyond the current state of the art.

The transformations to air traffic operations intended for NextGen may eventually rely heavily on automation. Machines may be assigned tasks currently assigned to humans. Tasks ultimately performed by humans may rely heavily on information integration and decision-making by machines, including the issuing of commanded trajectories to airplanes by machines. The continuing integration of automation dramatically changes a human's roles and responsibilities. New designs must be incorporated that prevent humans from being expected to monitor for faults in an automated system and intervene when that automation is performing a task beyond the human's capabilities.

While implementation of air traffic automation is currently limited to some decision aids for specific purposes, modern airliner, regional jet, and business jet flight decks are highly automated. The safe application of automation is not easy. Recent research with automated flight decks has shown that automation typically reduces some types of problems (e.g., high sustained workload for mundane tasks) but introduces others. Increased automation has led to notable accidents, such as the 1995 crash of American Airlines flight 965 near Cali, Colombia, in which the pilots mistakenly commanded the cockpit automation to fly to the wrong navigation aid, and the 1992 crash of AirInter flight 148 near Strasbourg, France, in which the pilots may have mistakenly commanded the wrong descent mode. The current state of the art in ensuring effective human-automation interaction largely centers on qualitative design principles for human-automation interface design and for function allocation.

Likewise, the increasing availability of information to pilots, controllers, air traffic managers, and other decision-makers via sensors, databases, and communications already establishes challenges in managing, filtering, representing the information, and using it to support effective decision-making. The last decade has seen the implementation of many new flight-deck displays, including synthetic vision, vertical profile displays, and electronic flight bags. However, audio and tactile display modalities (including synthesized voice of text, 3D audio displays of spatial information, and other auditory representations) provide additional display mechanisms that are not as well researched.

The challenge of managing this information is generally handled in two ways. First, in many systems, decision-makers are required to select or switch between multiple pages or representations. This design may foster active interaction with the information and improve situational awareness, but may also add to workload, causing users to get lost in the information or not be able to find information at the appropriate time. Second, alerts and "information pop-ups" generated according to predefined criteria direct attention to (and often present) information of a temporal nature only when that information is estimated to be relevant. Although these alerts and information display functions help to prioritize the most hazardous alerts in air transport aircraft, they are typically federated. Each provides information about a different phenomenon (e.g., weather, traffic, terrain, and navigation information on different displays) and the pilot is left to determine the relevance and priority of the various alerts. There have been problems with false alarms and the unintended use of such information.

The most significant display efforts at this time focus on representing fairly low-level information. Technology designed to facilitate equivalent visual operations often provides a picture of the world outside the cockpit without an overlay of information about aircraft performance and airspace requirements. This information is often presented on federated displays, leaving the human decision-maker to integrate and interpret the meaning relative to immediate and future goals.

Another information-management issue requiring attention is the distribution of information to multiple decision-makers. To date, efforts in this area have been largely and necessarily focused on providing mechanisms for sensing and communicating information so that decision-makers share the same inputs and "information-starvation" is avoided. However, current research shows that even when presented with identical information, disparate decision-makers such as pilots, controllers, and system managers are likely to consider different information elements, interpret and prioritize them differently, and make different decisions.

A further information-management shortcoming is a lack of shared situational awareness among NAS users. This can impede collaborative decision-making, lead to suboptimal flight planning, and limit the flexibility of the system and users to deal with changing operating conditions. A particular concern is the need to effectively predict, disseminate, and present weather information. As described in the mobility section, insufficient and uncertain weather information leads to disruptions, unnecessary flight delays, and inefficient allocation of NAS resources. These problems are compounded by the absence of common situational awareness of the weather information that does exist. NAS users rely on different sources of weather data, resulting in uncoordinated decision-making by stakeholders such as flight operation centers, pilots, controllers, and traffic managers. A lack of shared situational awareness about airport surface operations also leads to safety concerns. Operators and controllers have limited information about aircraft surface movements. What information they do have is not integrated with traffic flow management and cannot be easily shared among the stakeholders in a timely or useful manner. This lack of a shared situational awareness among NAS stakeholders can contribute to suboptimal safety and operations on the ground and in the sky.

A factor in safe vehicle operations is the ability to avoid, while offering resilience to, flight in hazardous conditions. Currently, all commercial aircraft and a percentage of GA aircraft are equipped with systems for detecting and displaying weather activity. Sensors for detecting clear-air turbulence and wake turbulence are also being examined but are not generally operational. Flight in icing conditions causing accretion of ice on the airframe from atmospheric liquid water content has been widely examined, with decades of research providing the basis for extensive certification standards, pilot training, and aircraft systems that can help shed or prevent accreted ice on critical surfaces. However, recent evidence suggests another icing phenomenon, icing within jet engines at higher altitudes due to high icewater content, can be a cause of multiple simultaneous engine events, including flameouts and shutdowns. The extent of this phenomenon has only recently been identified, and research is only beginning on the atmospheric conditions that can cause it, look-ahead sensors that can predict these conditions, on-board sensors that can detect icing within the engine, and engine design properties that make them less susceptible to internal icing.

Safety Risk Monitoring

The forensic engineering approach to safety risk monitoring of the mid- to late-20th century has led to tremendous safety improvements. But the ability to transform the safety of the aviation system through concentrated, focused interventions in the technology or operations of an aircraft is becoming increasingly difficult. Current safety risk monitoring is a process of gaining insights through an examination of aggregate trends in incidents and, in some cases, subtle changes in associated data. However, improved safety performance has led to declining incident data, and often the data available are not sufficiently predictive to illuminate further safety performance improvements.

The approach needed now is to use prognostics, in lieu of forensics, as the means of gaining insight. A prognostic approach uses data mining and knowledge-discovery tools applied to both quantitative flight data (such as collected from digital flight data recorders) and text data (such as incident reports). The challenge will be to use what has been learned from studying accident sequences to identify dominant failure precursors and their origins and to identify the situations or circumstances that promote the transition from precursor to event. This analysis will require statistical and expert modeling, applying both judgment and data to identify association between circumstances and undesired risk states.

Myriad voluntary and mandatory safety-monitoring efforts have been developed over the years to focus primarily on addressing known issues. Some examples include the Aviation Safety Reporting System[23] and Flight Operations Quality Assurance data.[24] Rather than

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[23] The Aviation Safety Reporting System (ASRS), http://asrs.arc.nasa.gov/, is codified in FAA Advisory Circular 00-46D.

[24] As defined in FAA Advisory Circular, 120-82, “Flight Operational Quality Assurance,” dated April 12, 2004.

being integrated to assess the overall aviation system, these safety monitoring efforts have been managed independently by the various entities across multiple aviation sectors. Risk analyses lacked standardization, were often time consuming, and were not always shared.

However, this pattern is changing with the development and implementation of the collaborative Aviation Safety Information Analysis and Sharing (ASIAS) system. A key element of ASIAS is integration of operational data-analysis capability and data-mining tools used to identify emerging safety concerns. Industry and government are evolving toward standardized data formats and systems that can apply the same analyses. ASIAS has enabled the ability to fuse geographic, operational, flight quality, and text-based system reports into an integrated database. This capability for retrospective event analyses will soon enable anomaly detection in current operating conditions and may be applied in the engineering process for future system designs. It will transform the current system of individual, isolated, incompatible safety databases scattered throughout government and industry into a true safety-analysis tool. Most importantly, this will transform safety management from a reactive to an operationally integrated, proactive mode that anticipates and resolves safety issues before they become safety problems.

Cabin Safety and Accident Survivability

Despite the excellent safety record for aviation today, accidents do occur. In the event of an accident, it is imperative the passengers and crew on board survive a crash landing by escaping from the aircraft in a timely manner. The aircraft must maintain its structural integrity, which includes having adequate, viable escape routes. Current aircraft designs are such that, without fire, the majority of the passengers can potentially survive the impact of a crash landing. In commercial aviation, for the current fleet, the bulk of the load-bearing structure is made from aluminum. These aircraft largely are able to maintain their structural integrity. Restraint systems and the design of the seat and interior fixtures, such as overhead bins, are designed to help minimize impact injuries to passengers and crew.

Stringent flammability standards are required by the FAA for cabin interior materials that could contribute to the spread of fire, including seat cushions and large surface area materials (sidewall, ceiling and partitions) designed to improve post-crash fire survivability. The plastics used to fabricate transport category aircraft cabin interiors are among the most fire resistant that are commercially available. Fire-detection, extinguishing, and suppression systems are required in inaccessible areas of the aircraft where there is a significant risk associated with an in-flight fire, most notably the engines and auxiliary power units, and some cargo compartments.

At present, nearly one-half of aircraft fatalities in impact survivable accidents are due to the effects of smoke and fire. Post-crash fires are supported from two primary fuel sources: the aircraft fuel, and the materials within the aircraft fuselage and cabin. A post-crash fire will impede safe evacuation and may result in only a few minutes of usable passenger evacuation time. For the current fleet, these issues are well understood. There are many examples of the safe evacuation of the passengers and crew in these types of accidents, such as the Toronto runway overrun incident in 2005. The new aircraft envisioned in the future, built with novel materials and configurations, will introduce new challenges in this area that will need to be addressed to ensure the safety of the flying public.

FUNDAMENTAL AVIATION SAFETY CHALLENGES TO OVERCOME

Shortfalls associated with the state of the art will have to be overcome to ensure safety during the decades ahead. The following major safety challenges were identified in the Plan:[25]

1. Monitoring and assessing the health of aircraft, at both the material and component level, more efficiently and effectively.
2. Rapidly and safely incorporating technological advances in avionics into the aircraft.
3. 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.
4. 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.
5. 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.
6. Ensuring safe operations for the complex mix of vehicles anticipated within the airspace system enabled by NextGen.
7. Enhancing the probability of passengers and crew to survive and escape safely when accidents do occur.

Table 4 shows which challenges apply to each of the four Aviation Safety R&D areas. Approaches to meeting the challenges in these four areas are examined briefly on the right.

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[25] The challenges listed within this chapter of this Technical Appendix are listed according to their appearance in the Plan. No prioritization or ranking is implied or intended by the order of presentation within the Plan or this Technical Appendix.

Table 4. Mapping Aviation Safety Challenges to Research Areas

	Vehicle Safety Goal 1	Safety Risk Monitoring Goal 2	Safer Operations Goal 2	Accident Survival Goal 3
Challenge 1	x			
Challenge 2	x			
Challenge 3	x			
Challenge 4		x	x	
Challenge 5			x	
Challenge 6			x	
Challenge 7				x

Vehicle Safety

Today's aircraft are safer than their predecessors, and it is anticipated that safety will continue to improve with each future generation of aircraft. However, next-generation and generation-after-next vehicles (such as blended-wing body [BWB] vehicles and cruise-efficient STOL vehicles) will pose their own unique safety research issues. Likewise, improvements in safety will demand more knowledge of many phenomena that will affect both current and future aircraft and will require new technologies with transformative capabilities to address the issues detailed in this section.

Several issues confound the further reduction in loss-of-control accidents. First, current knowledge of aircraft flight dynamics is largely focused on the steady aerodynamic effects found within a fairly limited flight envelope. Knowledge outside the anticipated flight envelope is difficult to obtain. Current knowledge and models are not able to comprehensively depict the rapidly changing flight dynamics experienced with loss of control. Uncontrolled flight conditions are difficult to assess due to the risk in placing actual vehicles in these conditions, even in controlled research conditions. Second, current knowledge of aircraft flight dynamics, and assumptions underlying methods and standards for flight-control design, are based on decades of experience with current tube-and-wing aircraft configurations. The behavior of novel aircraft configurations, especially in upset flight conditions, is only starting to be extensively examined.

Technologies to address loss-of-control accidents will likely be based on adaptive flight-control techniques. Current flight-control designs depend on predetermined control shaping and control gains (i.e., magnification of control surface commands in response to deviations from desired aircraft state). In contrast, adaptive flight-control techniques are intended to continuously and purposefully adapt their control shaping and gains to maintain a desired closed-loop behavior across a wide range of aircraft dynamics, both anticipated and unanticipated. Thus, the adaptive control's ability to safely control the aircraft is not limited to a narrow flight envelope and to an aircraft with no system failures or degraded structures. Current adaptive controllers have been demonstrated in a range of flight vehicles from small UAS to manned flight research vehicles, and a body of underlying theory is being established for their design. However, their implementation in production systems is currently limited to some guided munitions systems, such as the Joint Direct Attack Munitions (JDAM) smart steerable weapon.

One significant challenge to the further implementation of adaptive-control designs is in verifying and validating the behavior of adaptive controllers. Current methods of validating flight-control systems are based on knowledge of both the exact flight-control behavior and the aircraft behavior, such that their combined closed-loop behavior in each design flight condition can be proven a priori to meet specified performance measures such as stability margins. In contrast, the exact control behavior provided by an adaptive system can not be established a priori. Aircraft flight dynamics cannot be predicted in all flight conditions, especially those involving extreme attitudes, structural degradation, and other disturbances such as ice accretion. Adaptive control is intended to have the benefit of controlling aircraft in such conditions, in addition to the normal flight envelope.

At least two methods exist for proving the safety of adaptive controllers. The first method may require some combination of extensions of adaptive-control theory to establish metrics of their performance that can meet verification, validation, and certification methods intended for current flight-control systems. The second method may require new standards and metrics for verification, validation, and certification. Such methods may focus less on exact a priori knowledge of closed-loop behavior and more on proof that the adaptive element can only improve closed-loop stability relative to some standard over all possible flight conditions, even in the face of potential corruption within the adaptive element.

Likewise, there are several aspects to reducing structural and component failures and the hazards they create. First, new materials, fabrication methods, types of structures, and aircraft configurations all demand new knowledge about structure degradation over the many-decade lifetime of aircraft that are starting to be designed and built. For example, the aging and response to damage of composite and hybrid composite-metallic structures is not currently well understood, and these behaviors may vary depending on details of the composite layup, the material composition, and the fabrication method. In addition, new fabrication methods such as electron-beam free-form deposit of materials can create strong, lightweight structures; however, the distribution of internal stress within the material is not well understood, and thus current crack-propagation models may not apply. Developing this knowledge requires advances in both theory and experimentation, with understanding needed for a wide range of spatial scales ranging from the very small (i.e., atomistic) up through those used for modeling structures overall.

Structural and component failures may be reduced by new methods of inspection, or by improved understanding and usage of established NDE methods. One challenge of

NDE methods is reliably finding and characterizing faults in new materials and structural arrangements. Unlike cracks in metals, composites may have several failure mechanisms (e.g., delamination or localized fiber breakage) that have their own characteristic signature based on the structural arrangement and the NDE method used. To compound the difficulty, new materials and structural arrangements do not necessarily suffer damage in the same locations or by the same mechanisms as traditional metallic structure. For example, composite structures might delaminate on the inner skin of a wing panel due to a low-velocity impact on its surface, while a metallic wing skin typically faces cracking around the fasteners that attach it to the underlying structure. Because of these differences, successful application of NDE technologies requires an understanding of their implementation in a maintenance operation as well as the material and structures that are being maintained.

Looking further in the future, the hazard created by subsystem and component failures may be reduced or eliminated using health-monitoring techniques. An IVHM system could diagnose the state of degradation of the vehicle subsystems and components and alert the users before failures can occur. Such a system could also provide the ability to detect problems in flight, diagnose the underlying cause, and use prognoses of their impact to use the component differently or to modify the flight profile to maintain safe operation despite degradations in the vehicle's condition. However, such a system requires several advances. These include sensors that are more reliable; are non-intrusive; are suitable in terms of cost, weight, wiring, and power requirements; have longevity for widespread implementation across the vehicle; and are capable of operating in potentially harsh conditions such as high-temperature areas within propulsive systems. Real-time understanding and analysis of these sensors, especially to predict faults before they occur, requires knowledge of each system's nominal behavior and of the characteristics of each failure. This may require physics-based models of a large number of phenomena, or extensive data from test and earlier operation for comparison, or both. The collection of many data from distributed sensors, each of which produce uncertainty and may also fail, requires continual integration and mining of a large data set, a capability that is currently a research topic.

The hazard created by subsystem and component failures may be mitigated by the ability to correct the failure in flight. For example, self-healing materials currently being examined are a film on the outside of a structure that, when heated, may arrest crack growth long enough for the aircraft to land, and other materials that may expand to seal puncture wounds in pressure vessels or tanks. However, at this time these materials are only in the earliest stages of research.

Faults within avionics systems, due both to hardware failures and to software bugs, pose their own unique challenges. The ability to monitor for, and predict, degradation in hardware before a distinct failure occurs is a research field in its infancy. As noted earlier, the safety constraints on the current ability to verify and validate complex avionics systems, especially their software, effectively prohibit many innovations in their capability. New methods of verification, validation, and certification are required that are simultaneously cost-effective and increasingly capable. Such methods may need to focus more on design processes and on formal methods for comparing design principles and assumptions to the ensuing avionics products. Health-monitoring systems may possibly use detection of avionics faults to instigate backup systems or to revert to simple, robust behaviors; however, such systems themselves add another complex system that may introduce its own faults to the vehicle.

Safety Risk Monitoring

As noted earlier, there is a recognized need across the aviation industry to shift from the current, historic accident analysis to diagnostic and prognostic analyses that use system-wide safety information sources. Fully achieving this capability for proactive management of safety, whether in support of ASIAS or other systems, requires research in anomaly detection, statistical analyses, information sciences, text mining, data-driven prognostic modeling, and risk assessment. There are two major areas of concern related to addressing such issues. One area is gathering, managing, and integrating knowledge of relevant evidence from individual- and from multi-source analyses in response to safety-oriented queries. Designing an automated capability to gather evidence from diverse, distributed data sources will enhance discovery, identification, evaluation, and prediction of performance of any aircraft system, subsystem, or component.

The second area is modeling and monitoring system-wide issues spanning the airspace, including the aircraft, ground infrastructure, and the human in the system, such as the development of unstable or over-limit traffic flows. Current safety risk monitoring systems primarily examine safety issues contained within single aircraft or one aspect of the system. Expanding modeling and monitoring capabilities will pose new challenges. One challenge is to define the metrics of a safe airspace operation that can be assessed from the available measures airspace. Current and foreseeable future operations will involve considerable uncertainty and variability, hampering the distinction between normal and degraded conditions. Another challenge is to assess the vast amount of data available, in real time, in a coherent manner, despite the distinct characteristics of the constituent pieces.

Safer Operation of Vehicles

NextGen, especially in the far term, is intended to establish transformative changes to air and ground operations. Future operations will be characterized by a wider array of aircraft with greatly varied capabilities (especially considering UAS), operating in a higher density environment in order to meet the nation's air traffic capacity requirements. To enhance capabilities, NextGen is anticipated to rely heavily on automation both for the management and operation of the system, as well as for decision-making and control of single and multiple

UAS or other vehicles. There are several fundamental safety challenges that must be faced in the development of this automation. One is the verification, validation, and certification of complex software underlying such automation. However, in the far term, these issues must extend to address verification and validation of complex system operations, such as the emergent effects where safety viewed at the system level may be compromised even when all individual components are functioning according to specification. A diverse range of studies are currently evaluating many of the issues regarding the safety analysis, verification, and validation of complex NextGen operations and the systems to support future operations. Additionally, the need for an interagency evaluation of whether these studies will collectively address all potential concerns in this area has been recognized by the JPDO.

Another aviation safety challenge involves human-automation interaction. The inclusion of automation dramatically changes a human's roles and responsibilities. The current state of the art has demonstrated that automation changes could potentially place human operators into conditions with excessive analysis and task loading that compromise safety. For example, a human cannot be expected to monitor for faults in an automated system and intervene when that automation is performing a task beyond the human's capabilities. Thus, a significant challenge will be designing concepts of operation that can be monitored and performed by humans in degraded conditions.

Future automation design requirements will require a close synergy between the design of automation functions and assessment of human performance in interacting with those functions. Calls for dynamic function allocation between human and automation in response to the immediate situation will require more quantitative and systematic methods than currently exist for assessing the situation and for predicting the effectiveness of potential task allocations. Overall, systematic methods for analyzing data to identify potential human-automation issues, including problems with workload and with visibility of the automation's functioning, will be required to implement new automation concepts with confidence.

Information-management and decision-making technologies also pose several safety issues in the information-intensive, highly networked operating environment envisioned within NextGen. Beyond consideration of the new display mechanisms noted earlier in this section, new methods to better manage, represent, integrate, and interpret information relative to immediate goals and concerns need to be developed. Information-management systems also must recognize when information is relevant and present it to human operators in a manner that directs them to act as required by current circumstances while still managing their ongoing tasks without persistent interruption. These integrating and alerting functions may need to help the human operators interpret, prioritize, and manage their activities as the automation monitors and interprets the environment's changing dynamics.

As a notable example, there are several issues to address in developing the ability to integrate varied sources of weather information into the single authoritative source envisioned for NextGen. First, additional weather observation data are needed to provide a better picture of the weather. Expanding the use of weather observing systems, which may include sensors on the aircraft itself as well as ground observing stations, will increase the amount of available weather data. Next, methods are needed to integrate and display that information on the flight deck and for other users to support improved decision-making and shared situational awareness among all NAS stakeholders. The ability to translate measured and predicted weather conditions to impact on safety of the NAS is currently missing. The challenge will be developing the decision-support tools that will use the weather information for shared decision-making between air traffic management and the flight crew.

Finally, establishing shared decision-making about weather and other concerns within NextGen poses several safety issues. As noted earlier, current knowledge about shared situation awareness and collaborative decision-making suggests that, even when presented with identical information, disparate decision-makers such as pilots and controllers are likely to consider different elements of the information, interpret and prioritize it differently, and make different decisions. Thus, new models of collaboration and new collaborative technologies must be developed that foster communication not just of raw information and of resulting decisions, but also of intermediate interpretations and representations relative to individuals' goals and immediate situations.

Cabin Safety and Accident Survivability

Aircraft fire safety presents a number of difficult challenges that must be overcome. The plastics used to fabricate transport-category aircraft cabin interiors are among the most fire resistant that are commercially available. However, full-scale testing by the FAA has shown that an order-of-magnitude reduction in flammability compared with current materials is needed to eliminate in-flight fires and further improve passenger survival in a post-crash fire. This level of flammability reduction cannot be achieved with current materials technology, so targeted research is needed to develop lightweight, serviceable, and affordable aircraft cabin materials that are also ultra fire resistant.

Real or apparent in-flight fires often result in measures taken by crews that in and of themselves present a risk, such as diversions to unfamiliar airports, returns and overweight landings, and emergency evacuations. Part of the problem is the lack of verified information about the actual situation associated with a fire alert on an aircraft. The bulk of the in-flight visible smoke/odor incidents (more than 800 in 2006) are not fire related, but the crew will land the aircraft when presented a warning because it cannot determine the source of smoke or odor and will assume the presence of a fire.

Also, new technology presents new challenges related to fire safety and survivability. Composites increasingly are being used to make fuselages, wings, and other major aircraft structures. The replacement of noncombustible, thermally conductive aluminum with an organic, composite material that will burn under certain conditions and is a good insulator (a detriment under some fire scenarios) may increase the risk of in-flight fire or decrease post-crash fire survivability. Increased risk of fire resulting from the growing use of more energetic lithium batteries in passenger laptop computers and in aircraft systems also is a significant concern. These batteries may be supplanted in the future by fuel cells, potentially presenting an even greater fire-safety concern.

Aircraft with new structural configurations and made of new, advanced materials will need research to ensure that the structural integrity of the aircraft can be maintained sufficiently to protect the occupants in the event of an accident and to provide egress. Advanced computational techniques will also be needed to simulate complex, dynamic events (such as crashes) to minimize full-scale testing required to ensure the safety of these future aircraft. These simulations will be dependent upon technically advanced material models if the structure is made of new materials such as metallic composites, ceramics, and other non-heterogeneous materials that will have complex failure mechanisms. New aircraft designs may also require new occupant-protection systems to ensure adequate protection during normal operations and in the event of an accident.

The safety implications of alternative aviation fuels will need to be evaluated to understand their safety characteristics once these fuels are more fully developed. Post-crash fires are often precipitated by spilled aviation fuel, and fuel tank explosions such as TWA 800[26] are often dependent on fuel vapor characteristics. Since existing FAA fire test standards related to engine protection and cabin materials are based on the heat flux and temperature generated by burning Jet A fuel, these standards will have to be assessed and potentially enhanced to accommodate alternative (e.g., synthetic) fuels. This research topic is noted here, recognizing that such R&D depends upon the eventual development of viable alternate fuels.

SUMMARY OF R&D ACTIVITIES SUPPORTING SAFETY GOALS

Goal 1 – Develop technologies to reduce accidents and incidents through enhanced vehicle design, structure, and subsystems

The FAA is conducting research in structural health monitoring (SHM) for both fixed-wing aircraft and rotorcraft. For real-time SHM for transport aircraft, research will provide data needed to allow assessment of the state of SHM in commercial transport airplanes for current and NextGen applications, including fatigue monitoring and condition-based maintenance. This includes analysis and experiments for determining the ability of proposed SHM systems to perform structural diagnosis and prognosis. For rotorcraft applications,

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[26] "In-flight Breakup Over the Atlantic Ocean Trans World Airlines Flight 800 Boeing 747-131, N93119 Near East Moriches, New York, July 17, 1996," NTSB Report PB2000-910403, NTSB/AAR-00/03, DCA96MA070.

the FAA is developing guidance and technical information, including data for advisory circular and possible new regulatory material for health and usage monitoring systems (HUMS) certification. Outputs will include assessments of rotorcraft fatigue spectrums and mission profiles that will be used in damage tolerance, fatigue spectrum definition, assessments of pilot reactions (human factors) to warnings, and the initiation of maintenance actions due to HUMS warnings.

Additionally, major changes are taking place in the tasks and jobs that aircraft maintenance personnel must perform with the introduction of complex, computer-based aircraft. The advent of new technologies currently being introduced, coupled with the technologies envisioned by NextGen, will substantially increase maintenance complexity as satellite-, ground-, and air-based technologies become more integrated. Just as with operations personnel, R&D will be required to help define the roles and tasks required of future maintenance personnel to ensure a higher level of safety in this new environment. Current research is evaluating how maintenance personnel deal with the extensive computer-based health-monitoring systems that are now becoming available on new aircraft.

The FAA is conducting research for flight performance envelope protection for GA aircraft. This research task will develop minimum performance criteria and certification requirements for automatic envelope-protection systems, which do not yet exist in GA. The R&D will provide an initial assessment of ways that simple envelope protection could be implemented into the GA fleet in a cost-effective manner using current certified Part 23 avionics systems. The FAA seeks envelope-protection schemes and implementation procedures to reduce the number of controlled-flight-into-terrain and loss-of-control accidents for GA. The project will provide a knowledge base for developing policy, regulations, and guidelines for application and certification of systems that can be implemented using existing integrated avionics systems and autopilot technology. The output of this research task must specifically address technologies for retrofit into existing GA airplanes and may also address future technology applications for providing envelope protection to GA airplanes, such as full-authority digital flight controls. The information will also be used to foster support for such systems. The successful outcome of this work will be considered for applications on existing transport airplanes for retrofit and for UAS.

The FAA is planning a research program to study damage tolerance and durability of emerging technologies. This research will develop guidance and technical information, including data for emerging technologies (e.g., new aircraft structural materials) entering service, to help establish future certification standards necessary for aviation safety. Training and detailed technical background will also be established to support expanding applications and new rules, policies, and guidance. All the outputs combine to ensure safe implementation of emerging technologies in aircraft products.

The FAA has a research program for advanced material structures. Research is focused on damage tolerance and fatigue of composite airframes, as well as on the aging of composite materials. Composite control surface degradation on transport airplanes will be explored and linked to aircraft safety issues. Bonded joints will be studied for damage tolerance and durability. Researchers will also explore potential savings in maintenance costs associated with the use of embedded sensors to monitor in-service damage and will investigate the long-term safety of friction stir-welded parts and fiber/metal laminates proposed for use in new aircraft. In addition, they will collect data for new materials and applications, such as ceramics and high temperatures, respectively.

NASA's Aircraft Aging and Durability Project seeks to develop fundamental insights into the lifetime material properties of aircraft structures and materials. Research is focusing on physics-based models of degradation, including crack propagation, composite delamination, de-bonding of joints and materials, and impact strength. This modeling spans multiple scales from atomistic and molecular up to the grid resolution commonly applied in finite-element modeling of structures. Insight is sought not only about materials common in current-day systems, but also about likely future materials (e.g., hybrid composite-metallic or high-temperature alloys) and structures made with future fabrication methods (e.g., electron-beam deposit). This project also seeks to develop novel methods for non-deterministic evaluation in support of lifetime maintenance and management of vehicle structures, including wiring.

NASA's Intelligent Resilient Aircraft Control (IRAC) Project is focused on the myriad causes of aircraft loss of control. One major thrust of this project is to better understand flight dynamics and aerodynamics in upset conditions (i.e., at high angle of attack and/or sideslip). New methods of representing and modeling these unsteady dynamics are required to enable control-system design, flight-simulator testing and pilot training, and analysis of aircraft properties that improve or hinder upset recovery. NASA is addressing these issues through aerodynamic and flight mechanics models, simulator development and testing, wind tunnel and spin tunnel testing, and flight testing with dynamically scaled models.

NASA is also developing adaptive controller capabilities that can provide robust control through all flight regimes (including upset conditions), despite damage or degradation. Like others in the aviation control development community, NASA is developing and testing algorithms for adaptive control. As a comparatively unique contribution, NASA is also examining the implementation of adaptive control in flight-critical environments through flight testing and through hardware-in-the-loop simulations on full-scale, quad-redundant avionics architectures.

NASA's IVHM Project seeks to sense and monitor flight parameters to detect, diagnose, predict, and mitigate system failures. One aspect of the research emphasizes development of new sensors that can examine structural degradation in flight as well as other aircraft systems, including the hot section of propulsion systems, airframe and engine icing, and electrical systems. NASA is researching and modeling potential causes of in-flight degradation, including lightning, high-intensity radiation, and probabilistic models of progressive structural failures and gas-path dynamics within engines, and studying the use of sensor information to diagnose and predict problems and their impact on system integrity. Similarly, research is examining structures that can mitigate the effects of degradation through self-healing mechanisms providing sufficient life for a safe landing. The IVHM Project is also establishing the data-mining and automatic reasoning methods suitable for modeling multivariate data from multiple sensors, monitoring for trends and combining their insight to make better predictions, detections, and mitigations. These algorithms and tools can be applied to not only on-board systems, but also to off-line analysis of recorded data such as radar data, digital flight data recorder output, and fleet-wide databases including the ASIAS data set.

The IRAC and IVHM Projects are considering software as a vital part of the aircraft. As part of its research into complex control systems, IRAC is examining methods for verifying and validating flight-critical software. IVHM is examining methods for software health management by which the output of software is monitored in flight to detect latent failures and other erroneous output, ideally so that these errors can be isolated or corrected in flight.

DOD aeronautics R&D efforts are focused on providing advanced military aviation capabilities. However, safety of aircraft and airspace systems is critical to protecting airmen, soldiers, and civilian populations, as well as to ensuring operational availability of aircraft and successful mission accomplishment. As such, the DOD currently has projects whose end products enable progress to be made toward the near-, mid-, and far-term objectives in each of the aviation safety goals. Further, it is possible that many of the concepts and technologies being developed by the DOD may be leveraged for civil aviation applications.

In relation to Goal 1, the DOD has, and continues to pursue, a number of efforts focused on managing aircraft usage, safety, and accumulated damage. These projects have researched sensors and sensor architectures, damage prediction algorithms using data from multiple sources, and vehicle management architectures. The goal of these projects was not only to reduce the number of aircraft accidents and losses due to mechanical failures, but also to allow preventive maintenance to be performed and improve aircraft availability through enhanced maintenance-specific planning.

Current projects include an effort in adaptive vehicle management, which is focused on improving the platform robustness while maintaining safety and platform reliability under off-nominal conditions (i.e., degraded and/or damaged vehicle; adaptable to mission equipment packages and system health changes), and a prognosis effort, which is developing novel physics-based models and advanced interrogation tools to assess damage evolution and predict future structural performance. These project goals will be realized through techniques that will enable flight controls to use multiple platform subsystems as data sources and then modify vehicle system software to auto-adapt the aircraft's vehicle management system in response to aircraft health and operational changes during flight.

Another key aspect to making aircraft safer and less expensive to operate is developing materials that perform better under challenging fatigue and corrosion environments. The DOD is investing in multiple materials development projects that have the potential to provide materials with prolonged lifetimes and tailored properties based on environment. For example, a hybrid structures project is investigating replacing monolithic aluminum with alternate materials. This project will also develop design and analysis tools that will allow optimal material selection and placement and reduce certification time and expense.

Goal 2 – Develop technologies to reduce accidents and incidents through enhanced aerospace vehicle operations on the ground and in the air

The ASIAS project, supported by the FAA, NASA, and several airlines, seeks to deploy, operate, and maintain distributed, net-centric archives of airline industry flight data and safety reports. ASIAS will develop innovative, advanced tools and methodologies that, for the first time, will be able to convert and integrate digitally recorded or textually reported aviation safety data that is distributed across operating organizations and archives into information on the operational performance and safety of the aviation system. A key element of this integration is the identification of system characteristics/precursors or conditions conducive to human error. The objective of ASIAS is to demonstrate a common, time-delimited working prototype of net-centric information and shared applications extracted from diverse, distributed sources of data and legacy tools. This research program will provide: (1) automated tools to monitor each database for potential safety issues and to analyze disparate data drawn from multiple sources, enhancing discovery, identification, and evaluation of safety risks; (2) advanced software (middleware) capable of automated gathering of supporting evidence from other databases and of integrating historical data with data from ongoing air transportation operations; and (3) prototypes of cutting-edge data-analysis tools that enhance automated and human identification of precursor elements in the air transportation system that can be monitored for prognostic estimates of trends in safety.

The FAA, NASA, industry partners, and potentially foreign research agencies, are collaboratively preparing a set of flight campaigns to locations thought to provide the greatest opportunity to characterize atmospheric conditions with high ice-water content—conditions that are consistent with recent engine power-loss incidents hypothesized to result from icing internal to the engine. The campaigns will also provide an opportunity to examine sensors detecting icing on the aircraft and within the engine and predictive sensors forecasting potential icing conditions in the upcoming flight path.

The FAA is planning a research program studying human factors issues related to air traffic operations for controller efficiency and air-ground integration. In the area of controller efficiency, the FAA will address human-system integration and human-performance issues related to achieving increased capacity without a commensurate increase in the number of air traffic service providers. It will examine how air traffic service providers can benefit from future automation capabilities to safely achieve higher efficiency levels through the integration of air traffic control and aircraft automation, decision-support tools, workstation displays, and procedures in future operations.

In the area of air-ground integration, the program will examine the ability to enhance and redefine the scope of the traditional air traffic controller (ground) and pilot (aircraft) communication, separation, and control responsibilities in future air traffic service provision. For pilots, the research will focus on ensuring that the appropriate information is provided in a format and time frame that enables the ability to ensure correct and timely decisions. For air traffic controllers, the research will address enabling enhancements to air traffic service provision by controllers in light of potential evolutions to aircraft capabilities. Through the use of modeling, simulation, and demonstration, the program will assess the interoperability of tools, develop design guidance, determine training requirements, and verify procedures for ensuring effective and efficient human-system integration in the transition to NextGen capabilities. Research will also address changes in responsibilities and liabilities and examine new types of human error modes to manage safety risk.

As adaptive-control techniques are developed, FAA research will assess factors driving pilot performance and will consider transfer of training from various classroom methodologies on the ground to operations in static and dynamic simulators emulating physiologically stressful flight conditions (e.g., acceleration, altitude, aerobatic maneuvers) and ultimately in flight.

The FAA Aviation Weather Research Program will provide weather observations, warnings, and forecasts that are more accurate and efficient to a wide variety of users. The results of this R&D effort are focused on improving near-term and mid-term forecasts of naturally occurring atmospheric hazards, such as turbulence, severe convective activity, icing, and restricted visibility. Improved forecasts enhance flight safety, reduce air traffic controller and pilot workload, enable better flight planning, increase productivity, and enhance common situational awareness.

The FAA research program, Weather Technology in the Cockpit, will be conducting research to develop technical data and information to enable the development and use of improved flight-deck weather information technologies. The research will lead to policy, standards, and guidance for the display of weather information and its use, including design guidance, training, procedures, and error management. Using these technologies, pilots and aircrews will have shared situational awareness and shared responsibilities with controllers, dispatchers, Flight Service Station specialists, and others for weather-related aviation safety decisions before, during, and after flights.

The FAA is planning to conduct research for system safety assessments. The research will develop a prognostic safety-assessment tool capable of evaluating NAS-level safety impacts resulting from new NextGen concepts. It will include both new technology and procedural system modifications that emerge from the three FAA NextGen Implementation Domains, including the seven solution sets within the Air Traffic Organization Domain (ATO). The approach will build a tool (or expand upon an existing tool) that will use causal models to conduct system-wide safety risk assessments. The intent is to assess the full spectrum of flight operations for the entire NAS. However, the concept demonstration will assess a subset of the NAS, along with selected new technologies or procedures, and initially focus on capabilities proposed within the seven ATO solutions sets. Subsequent work will address the broadening of the tool to provide a full NAS-wide assessment capability.

NASA's Integrated Intelligent Flight Deck Project is examining fundamental issues with human-machine integration in far-term NextGen concepts of operation. While focused on the flight deck, the project recognizes that the flight deck cannot be considered in isolation. Communication and collaboration between air and ground are integral to flight-deck research. One focus of this project is developing robust human-automation interaction concepts that can effectively support human performance while taking advantage of automated capabilities and that can effectively operate even in off-nominal or degraded situations. Another focus is examining information management in support of decision-making, both individual and collaborative. This work is collaborative, with other FAA and NASA projects focused on design of NextGen concepts of operation and capacity-enhancing technologies as noted in the Mobility chapter.

Of specific concern is the consideration of weather information in decision-making in NextGen operations. NASA is supporting the coordinated interagency (noted earlier) flight research of atmospheric conditions conducive to, and sensing of, high ice-water content conditions hypothesized to lead to engine icing. NASA also is examining a range of sensors to detect hazardous weather conditions, including clear-air turbulence, wake turbulence, liquid-water content conducive to airframe icing, and convective weather. The integrated alerting possible from a combined suite of sensors, database information, and information transmitted to and between aircraft is also being considered.

Improving aircraft and airspace operations is a key element for reducing accidents in accordance with Goal 2. One effort currently underway at the DOD is developing an adaptive expert system to automatically detect and rapidly analyze aircrew performance to detect human factors-related mishap leading indicators. The effort includes development of a feedback mechanism so the expert-system adaptation process can take place by using anomaly detection and corroboration. Additionally, there are a number of projects currently underway with regard to integrating UAS into airspace with manned systems. Key efforts include investigating the means to allow crewed and uncrewed aircraft to operate safely in the same airspace at both low altitude and at medium and high altitude. Another program will maximize airspace utilization through dynamic military airspace management. It will also investigate a means to reduce the labor-intensive, human-centric airspace management processes that result in inefficient use of airspace and limit the density and responsiveness of airborne systems. Challenges to be addressed include complex algorithms and network information exchange and integration with legacy, degraded, and intentionally disruptive aircraft. The program will also explore novel concepts of operation enabled by radically enhanced airspace utilization. Another project is developing and demonstrating technologies for ground operations of UAS at shared manned airbases. Potentially, some of the technologies that enable UAS to operate with manned aircraft in ground operations have applicability to manned aircraft ground operations. Finally, the DOD is looking at ways to improve flight deck displays to improve pilot situational awareness. One key project in this area is tasked with developing the improved information displays to allow safer operations in poor weather or limited-visibility conditions (e.g., whiteout or brownout conditions).

NSF is supporting research in embedded sensing and control systems and in science and technology for high-confidence safety- and security-critical systems in several domains, including aviation. Research in hybrid (discrete and continuous) control research and its stochastic variants seeks to bridge the gap that has existed between traditional continuous mathematical control theory and software-enabled control and systems technology, for complex, adaptive, multimodal fly-by-wire systems. Likewise, proposed research areas seek to unify areas previously addressed in a more stovepiped manner, such as software safety analysis, formal verification methods, distributed control, real-time systems, fault tolerance, and systems-level software (OS, middleware) research. NSF supports research in improved methods and technology for certifiably dependable critical systems. The focus so far is on modular design, verification, and validation via formal methods and systems theory.

NSF is planning a new cross-directorate program on Cyber-Physical Systems to help research the information-technology and engineering challenges that are emerging in open, networked physical and engineered systems, such as airspace systems. Plans include new approaches to adaptive and predictive cyber control that will be both widely and deeply integrated into the complex, networked, engineered subsystems and systems expected in the future. The approach to shared authority and orchestrated cyber and human interaction with, and operational control of, systems are among the concerns.

Goal 3 – Demonstrate enhanced passenger and crew survivability in the event of an accident

FAA Crashworthiness and Aeromedical Research will establish design criteria for restraint systems that protect occupants at the highest impact levels that the aircraft structure can sustain. This includes developing and validating mathematical models to evaluate whether aircraft designs meet requirements for evacuation and emergency response capability and developing mathematical models addressing human survival from aircraft crashes. Dynamic testing and modeling tools will be used to establish parametric and non-parametric relationships. The injury potential of various aircraft materials, configurations, and protective systems will be assessed.

The Aeromedical Research Program is developing impact seat and restraint standards, design and certification test methods, and bioengineering criteria to optimize occupant survival at maximum airframe impact tolerance. Research is aimed at enabling the insertion of new technologies into certified civil aviation products and their operations by conducting tests emulating crash situations using advanced bioengineering techniques and anthropomorphic test dummies to represent a wide array of the human population. This will lead to a better understanding of crash environments, including head impact, seat deformation, occupant restraint performance, and optimum airbag placement and configuration. The research will provide recommendations that help define safety requirements in the early stages of product design and development to reduce costs and ensure earlier initial operational capability for hardware, software, and procedures.

The Aeromedical Research Program is also addressing pre- and post-crash survival emergency procedures by conducting tests that simulate emergency egress situations. These tests will assess issues such as aircraft exit size and location; design of emergency escape slides; passenger and aircrew behavior; passenger information requirements; the clarity and utility of signs and symbols used in passenger safety information; and the performance of communications, survival, and emergency equipment. Research includes developing mathematical models to predict human survival from aircraft crashes and using dynamic testing and modeling tools to establish parametric and non-parametric relationships to assess the injury potential of various aircraft materials, configurations, and protective systems.

The Civil Aerospace Medical Institute (CAMI) has developed a methodology to compile, classify, and assess aviation-related injuries, the sources of these injuries, and their relationship to autopsy findings and medical certification data. CAMI is also conducting research aimed at improving the identification and assessment of emerging safety issues by organizing and managing aeromedical system data. CAMI mines the data to assess pathologies, medications, and other aeromedical issues (e.g., diabetes, cardiovascular disease) and their significance to aviation safety, including advances in disease monitoring and treatment modalities.

In the FAA Fire and Cabin Safety Program, near-term research will focus on improved fire test standards for aircraft interior materials that cause or contribute to the spread of hidden in-flight fires. Hidden materials that will be targeted include electrical wiring and air conditioning ducting (new fire test standards for thermal acoustic insulation were previously developed and are now a regulatory requirement). The use of new fire-resistant, lightweight magnesium alloys to replace aluminum in seat structures and other aircraft applications will be evaluated under full-scale, post-crash fire test conditions. Fire test criteria will be developed, if appropriate. In addition, research will be conducted to develop new polymers or flame retardants that do not incorporate halogenated compounds that have been banned in Europe because of environmental and health concerns. The effect of structural composite fuselages and wings on fire safety in new large transport aircraft will be examined under full-scale, simulated in-flight and post-crash fire conditions. In particular, a fire test standard will be developed to safeguard against in-flight fires impinging on a composite fuselage, and fire test criteria will be developed to limit the emission of hazardous gases into the cabin during post-crash fire exposure of a composite fuselage. Additionally, long-range research will be conducted to develop the enabling technology for a fireproof aircraft cabin constructed of ultra-fire-resistant materials that offer a factor of 10 reduction in heat-release rate compared with contemporary interior materials. The FAA is also developing analytical procedures to assess the smoke toxicity of advanced materials.

NASA's SRW Project is examining issues similar to FAA and NASA efforts as applied to rotorcraft. In addition to examining HUMS jointly with the FAA, SRW also has near-term efforts in rotorcraft dynamic impact modeling and mid- to far-term efforts in rotorcraft crashworthiness.

Current focus of DOD R&D on crash and accident survivability is directed predominantly toward rotary-wing aircraft. Research is ongoing to improve the analytical tools to allow multipoint design of structures and better predict the effect of varied surfaces and payloads on the crashworthiness of current and future designs. Prototype automatic energy attenuators, smart landing gear that adjust performance to aircraft velocity and weight, advanced inflatable restraint-system components, improved crashworthiness design criteria, and active energy-attenuation control are also being developed with an eye toward further development and incorporation into future and current designs, as applicable.

ANALYSIS OF OPPORTUNITIES WHERE ADDITIONAL R&D FOCUS MAY BE WARRANTED

The Aviation Safety aeronautics R&D goals and objectives were assessed in light of the activities described in this Technical Appendix to identify areas of opportunity for potential increased emphasis as well as potential areas of unnecessary redundancy. The methodology for this assessment considered the previously described four key issues:

- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the near term;
- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the mid to far term;
- The level of coordination among executive departments and agencies; and
- The level of redundancy of efforts among executive departments and agencies.

Each of these four areas was given a broad assessment of green, yellow, or red based on this review. A green assessment denotes that R&D activities planned or ongoing are sufficient to achieve the objectives in the time frame indicated, that there is strong coordination among executive departments and agencies, and that there is no unnecessary redundancy. A yellow assessment indicates that R&D activities should provide significant progress toward the objectives but there is some risk due to fiscal or other constraints that merits continued attention, that coordination is taking place but could be improved, or that there does not appear to be unnecessary redundancy but additional coordination may be warranted. A red assessment highlights an area where additional emphasis or improved coordination among executive departments and agencies may be warranted to achieve the objective. The overall results of this analysis are shown in Table 5 at the end of this section.

As shown in Table 5, significant progress is expected toward all Aviation Safety aeronautics R&D objectives in the near term, and adequate coverage is planned for the mid and far terms with one exception—the ability to validate future design and analysis tools for integrated vehicle structure and occupant restraints because of insufficient foundational research. Each of these areas is addressed in more detail under the associated goal below.

Goal 1 – Develop technologies to reduce accidents and incidents through enhanced vehicle design, structure, and subsystems

With continued vigilant focus, R&D planned for this goal is adequate. Near-term research in IVHM of structures and propulsion systems is being conducted by NASA, the FAA, and the DOD. Additionally, NASA is conducting research toward this goal’s far-term objectives and examining the health management of a wide-range of aircraft systems, including software. The degree of coordination required across the large number of research projects related to vehicle health management, spanning several agencies, remains challenging. Far-term research in this field is based on projections of likely future vehicle characteristics; the rapid emergence of new technologies may require new research to examine its health management.

NASA and the DOD are conducting research into adaptive-control mechanisms. R&D includes near-term demonstrations of the efficacy of adaptive-control mechanisms and far-term research into validation through flight research and formal methods. Additionally, far-term research will ensure that adaptive control does not conflict with similar functions in guidance and trajectory planning occurring at different time scales. Similar to vehicle health management, interagency coordination is challenging, especially given that adaptive-control applications may extend beyond safety objectives.

Research into material degradation, and corresponding far-term research into methods to design structures and materials with extended life, is coordinated by the Joint Council on Aging Aircraft (JCAA), which includes several entities within the DOD, the FAA, and NASA. JCAA organizes an annual conference and focused steering groups specializing on specific aircraft components. Near-term research in this area is generally focused on the materials and structures in current-day aircraft. Far-term research in this field is based on projections of likely future vehicle characteristics; the rapid emergence of new technologies may require new research to examine their aging and durability.

Interagency coordination of safety-related research is hampered by different perspectives on safety and organizational approaches, such as whether safety-related research is consolidated in a single research program or distributed over other research areas. Emerging coordination is evidenced by attendance at recently founded conferences in Systems Health Management and in Prognostics Health Management.

Goal 2 – Develop technologies to reduce accidents and incidents through enhanced aerospace vehicle operations on the ground and in the air

With continued vigilant focus, R&D planned for this goal is adequate. Near-term research into human-systems integration is being conducted by the FAA and NASA, largely concentrating on the most immediate aspects of NextGen operation. The FAA is also conducting mid-term research into human-machine interfaces in support of mid-term NextGen developments. Likewise, NASA is conducting mid- and far-term research into flight-deck systems that support far-term NextGen operations, with a particular focus on robust automation-human systems and on information display and decision-making. NASA will be challenged by the potential complexity of the far-term research into human-automation interaction and human-machine interfaces for air traffic systems. Human-automation interaction and interfaces for air traffic systems R&D work is specifically coordinated through periodic integration meetings and joint reviews. An additional challenge is that NASA's ability to conduct research in this area will need to be balanced against competing priorities that may limit the resources needed for extensive high-fidelity simulations.

Near- and mid-term research at the FAA and NASA is seeking flight-deck systems to improve decision-making about weather. Likewise, the FAA is examining ground-based methods of observing weather phenomenon and of integrating diverse sources of weather information; NASA is developing airborne sensors for atmospheric hazards including icing conditions, turbulence, and convective weather activity. NASA's far-term research supports the goals of this method through advanced flight-deck technologies, including systems to replan flights with consideration for weather. However, this research examines broader concerns with air-ground coordination and decision-making without an exhaustive consideration of all weather concerns. No formal mechanism is currently in place to coordinate FAA and NASA research in this area. An additional challenge is that NASA's ability to conduct research in this area will need to be balanced against competing priorities that may limit the resources needed for extensive high-fidelity simulation capabilities and for flight research vehicles for sensor testing and development.

NASA's role within the joint ASIAS project is to provide the tools to better analyze narrative text and flight data, including flight data recorder, weather, and radar data. The requirements for, and implementation of, these tools are carefully coordinated through the ASIAS Executive Board. NASA's ability to conduct this research may be limited by constraints on access to the proprietary and sensitive data sets (largely belonging to airlines) that the tools are intended to examine. This ability to examine for single-vehicle behaviors is also extended by NASA (and some sponsored academic research) into examining definitions and metrics of degradation in large-scale distributed systems that can be monitored in real time, and methods of automatically detecting and recovering from such degradation. The FAA System Safety Management Transformation effort is also examining mid-term research goals to improve automated information analysis and prognosis capabilities.

Goal 3 – Demonstrate enhanced passenger and crew survivability in the event of an accident

The individual D&A plans partially address the first Goal 3 objective to develop occupant design tools. Near-term R&D at the FAA is directed at ensuring the occupants will survive a crash by enabling the development of enhanced occupant-restraint systems. The DOD also has research focused on enhancing rotorcraft crew and passenger survivability in a crash environment with energy-absorbing structures. The combined agencies' timelines are adequate to achieve the objective in the near term.

However, the D&A plans could benefit from better coordination though no redundancy was identified. Foundational research in this area at DOD and NASA is focused on rotary-wing aircraft. There is limited foundational research to achieve the mid- and far-term objectives for other classes of aircraft, including large air transport passenger aircraft.

For the second objective under Goal 3, the individual D&A plans partially address the development of analytical methodologies to model dynamic events needed to achieve this objective. As with the first objective, the combined agencies' timelines are adequate to achieve the objective in the near term. The D&A plans are partially coordinated, with no redundancy identified. The near-term plans require continuous focus because the planned level of foundational research will challenge the timely achievement of the mid- and far-term objectives.

Completion of the mid- and far-term objectives for the third objective under Goal 3 will be challenging. Currently, the FAA is the only agency planning research in this area. Planned R&D activities by the FAA are adequate to achieve this near-term objective under Goal 3. However, FAA research is focused on near-term activities, with limited foundational research focused on the mid- and far-term objectives; consequently, those objectives are at some risk of completion. Because the FAA is the only agency with R&D planned in the area, there is limited interaction at the working level between the FAA and other agencies.

SUMMARY

Department and agency plans are adequate to achieve all near-term objectives. Interagency coordination of safety-related research is hampered by different perspectives on safety and organizational approaches, such as whether safety-related research is consolidated in a single research program or distributed over other research areas. As a consequence, continued attention is warranted to improve interagency coordination and prevent unnecessary redundancy.

Table 5. Aviation Safety Opportunities Analysis

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)	Near Term Objectives	Interagency Coordination	Redundancy	Mid and Far Term Objectives
Goal 1 Develop technologies to reduce accidents and incidents through enhanced vehicle design, structure, and subsystems	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	G	Y	Y	G
	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	G	Y	Y	G
	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	G	G	G	G
Goal 2 Develop technologies to reduce accidents and incidents through enhanced aerospace vehicle operations on the ground and in the air	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	G	G	G	G
	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	G	Y	G	G
	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	G	G	G	G

Table 5. Aviation Safety Opportunities Analysis—continued

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)	Near Term Objectives	Interagency Coordination	Redundancy	Mid and Far Term Objectives
Goal 3 Demonstrate enhanced passenger and crew survivability in the event of an accident	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	G	Y	G	R
	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	Y	Y	G	Y
	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	G	Y	G	Y

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 AND BACKGROUND

Since the energy crisis of the 1970s, almost all of the energy, aircraft, and engine companies, as well as government entities, have been investigating the use of alternative fuels in aircraft, albeit at a relatively slow pace given low conventional fuel costs or environmental drivers. However, growing concerns about the future availability of jet fuel and rising prices, along with growing concerns regarding air quality and global climate impacts, have inspired resurgent interest in alternative aviation fuels. At the moment, the largest driver for industry adoption of alternative fuels is the high and unpredictable cost of petroleum. The dramatic rise in U.S. fuel prices in the summer of 2008 caused intense concern in the aviation industry. In the summer of 2008, petroleum was priced at more than $140 per barrel, which led to fuel prices of over $5 per gallon.[27] Although petroleum prices have subsequently declined, the price of oil is expected to increase in the future. The U.S. Air Force consumed over 2.6 billion gallons of aviation fuel in FY 2006, costing about $5.8 billion. Every $10 per barrel increase in the price of oil drives up its fuel costs by over $600 million per year. For the U.S. commercial aviation sector, every 1 cent increase in fuel price translates into a $190 million cost to the industry per year. [28] National and international stakeholders have urged government, industry, and academia to coordinate proactive steps to meet these energy availability challenges.

A key energy issue that goes hand in hand with fuel cost and availability is aviation fuel efficiency. The U.S. commercial aviation sector has realized efficiency improvements in recent years. Compared with 2000, U.S. commercial aviation is moving 12% more passengers and 22% more freight while burning less fuel. Reduced fuel burn will lead to reduced emissions, including carbon output. Since 2000, the restructuring of U.S. airline fleets in the aftermath of September 11, 2001, rise in fuel costs, use of fuel efficient aircraft technologies, and improvements in air traffic management technologies and operational procedures have all contributed to these savings. This compares favorably with the U.S. economy overall, and aviation has outperformed automobiles in improving its energy

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[27] J. Hileman, D. Ortiz, N. Brown, L. Maurice, and R. Rumizen, "The Feasibility and Potential Environmental Benefits of Alternative Fuels for Commercial Aviation" (Anchorage, Alaska: International Congress of Aeronautical Societies, September 2008).

[28] Air Transport Association, http://www.airlines.org/economics/energy/.

intensity in the past few decades.[29] Improved fuel efficiency eases demand for petroleum and reduces fuel costs. It also has a positive impact on the environment since reducing fuel burn directly correlates to reduced direct greenhouse gas emissions and can also reduce air quality impacts. Efficiency gains can be found at the aircraft level, such as improvements in aircraft fuel efficiency, as well as at the airspace system level. There are three ways to improve aircraft fuel efficiency: increase aircraft lift-to-drag, reduce engine specific fuel consumption, and reduce airframe and engine weight. Significant R&D efforts could shift the current paradigm of standard tube-and-wing configurations with high-bypass turbofan engines and result in dramatically more efficient aircraft, while simultaneously reducing noise and emissions. Similarly, systemic improvements in ground, terminal, and en-route operations could lead to reduced flight hours, resulting in fuel savings as well as operational efficiencies.

Aviation energy concerns are not limited to alternative sources of jet fuel and improving aircraft fuel efficiency. Both airbases and airports have similar power grid and consumption requirements that also demand alternative energy and energy efficiency approaches. More efficient aviation facilities could increasingly use renewable energy sources rather than traditional sources of commercial power, leading to cost savings as well as reduced environmental impacts. Therefore, it is important to continue to invest in and implement technologies and processes that reduce airport and airbase energy consumption and diversify energy sources.

In addition to energy concerns, the environmental impacts of aviation comprise a number of key challenges. Despite technological advances during the last 40 years, aircraft noise still affects people living near airports, and aircraft emissions continue to be an issue locally, regionally, and globally. Aside from health and welfare impacts, aircraft noise and aviation emissions are considerable challenges in terms of community acceptance of airport capacity expansion. These challenges are anticipated to grow.

Noise concerns include takeoff, landing, taxi and engine run-up, flyovers of very quiet areas at cruise altitude, and sonic booms associated with supersonic flight. Aviation noise is primarily a quality-of-life issue for the public that impacts health and welfare, disrupts sleep patterns, and interferes with speech and learning processes in children. Noise can also impact property values and remains the primary environmental concern that undermines efforts to increase airport capacity.

National Ambient Air Quality Standards (NAAQS) for ozone and particulate matter (PM) in the United States were recently tightened and a continuing trend in this direction seems

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[29] J. Hileman, D. Ortiz, N. Brown, L. Maurice, and R. Rumizen, “The Feasibility and Potential Environmental Benefits of Alternative Fuels for Commercial Aviation” (Anchorage, Alaska: International Congress of Aeronautical Societies, September 2008).

likely. Within the ground transportation sector significant emissions reductions are being achieved through requirements for cleaner fuels and more stringent emission standards for cars and light trucks, heavy-duty trucks and buses, and off-road vehicles and engines. Though small by comparison, aviation's contribution to emissions that impact local and regional air quality is projected to increase along with activity, and eventually become a more prominent contributor as emissions from other sources within and outside of the transportation sector continue to decline. Furthermore, many state and local authorities are looking to airports for a portion of the additional regional emission reductions needed to meet the NAAQS.

While energy efficiency and local environmental issues have traditionally been the primary drivers of aeronautics innovation, the current and projected effects of aviation emissions on the global climate are a serious long-term environmental issue facing the aviation industry.[30, 31] Climate change and changes in land use and demographics will affect important human dimensions, especially those related to human health and welfare. In the future, with continued global warming, heat waves and heavy downpours are likely to further increase and intensify. Cold days and cold nights are likely to become less frequent over North America with substantial areas of North America likely to have more droughts with greater severity. Hurricane wind speeds, rainfall intensity, and storm surge levels are likely to increase. Other changes include measurable sea-level rise.[32]

The climate impacts of aviation emissions include: (1) the direct climate effects from carbon dioxide (CO_2) and water vapor emissions, (2) the indirect forcing on climate resulting from changes in the distributions and concentrations of ozone and methane as a consequence of aircraft nitrogen oxide (NO_x) emissions, (3) the direct effects (and indirect effects on clouds) from emitted aerosols and aerosol precursors, and (4) the climate effects associated with contrails and cirrus cloud formation. In addition, aircraft NO_x released in the upper troposphere and lower stratosphere may have a more significant impact on climate than ground level emissions.[33] Flight in the stratosphere also contributes to ozone depletion. Assessing the overall impact of aviation on climate, and quantifying the potential trade-offs of changes in aircraft technology or operations, is predicated on metrics to place these different climate impacts on some kind of common scale. Because of the uncertainty in understanding the scale of the indirect impacts of aviation on climate, appropriate technological, operational, and policy options for mitigation of these indirect impacts remain uncertain. Currently, aircraft-induced cloudiness, comprising both contrail cirrus and

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[30] Intergovernmental Panel on Climate Change Special Report, "Aviation and the Global Atmosphere," 1999.

[31] J. Waitz, J. Townsend, E. 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.

[32] U.S. Climate Science Program, Synthesis and Assessment Product 4.6, "Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems," July 2008.

[33] Intergovernmental Panel on Climate Change Special Report, "Aviation and the Global Atmosphere," 1999.

modification of cirrus by aircraft exhaust soot emissions, remains the most uncertain component in aviation climate impact assessments. The impact of aircraft-induced contrails and cirrus clouds requires continued investigation, since it could be a significant component in aviation's contributions to climate change.

The Clean Air Act authorizes the EPA to regulate greenhouse gas emissions from new motor vehicles in the event that the EPA determines such emissions contribute to climate change.[34] Although the implications of this ruling for aviation are unclear, it certainly points toward the need for aviation to continue its commitment to improving fuel efficiency. Within the United States, numerous state and local governments are taking action to address greenhouse gas emissions, yet this country is not the only force in this arena. Pressures on the world's airlines are increasing as market-based measures and other legislative initiatives to reduce greenhouse gas emissions from the aviation sector are adopted by various countries. With the expected growth in international air transportation demand, all of these factors will lead to increasing pressure to seek environmental-impact reductions from aviation-related sources. Despite the importance of this issue, until recently the United States did not have a significant research program to assess and investigate options for mitigating these impacts of aviation on climate. A step toward addressing this deficiency was the establishment of the Aviation Climate Change Research Initiative (ACCRI) to enable strong U.S. participation and influence in international scientific forums to improve the scientific understanding and modeling capability to assess aviation climate impacts and reduce key uncertainties associated with these impacts. This is critical to help ensure continued U.S. aviation competitiveness in world markets.

The effect of airport operations on water quality is also important, particularly impacts of storm water runoff from deicing operations. Since commercial airports and military bases within the United States will continue to be subject to the requirements of Clean Water Act regulations, water quality impacts need to be quantified and, if necessary, mitigated.

There is no identified single technological or operational solution to advance the goals of energy diversity and security, growth of aviation, and reduction of aviation environmental impacts. Yet, with research breakthroughs and coordination among key stakeholders, many opportunities for near-, mid-, and long-term improvements can be realized. There are many emerging technological, operational, and policy opportunities that can support a balanced approach to enhancing energy diversity and security and reducing the environmental impacts of aviation. It is essential that there be an integrated approach that addresses the interdependencies within and between these areas. A critical requirement to enabling new solutions is the development of better metrics and analytical models and

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[34] See *Massachusetts v. EPA, 127 S. Ct. 1438, 1459-60 (2007)*. Under the Clean Air Act, the EPA and FAA share responsibilities for the overall regulation of aircraft engine emissions with EPA establishing the standards (in consultation with the FAA on safety and noise considerations) and the FAA enforcing those standards typically through the airworthiness certification process.

tools for assessing interdependent impacts, and of options for addressing them. As they are developed, these models and tools should be used to assess the many opportunities for near-, mid-, and long-term energy production and use, and energy efficiency and environmental improvements that exist in the domains of technology and operations.

This energy/environment appendix of the Plan focuses on the linked policy principles of: (1) assuring energy availability and efficiency as central to the growth of the aeronautics enterprise; and (2) protecting the environment while sustaining growth in air transportation. This Plan builds upon the framework outlined in a report submitted in 2004 to Congress by the FAA and NASA,[35] and examines considerations beyond those previously emphasized. In addition, the Plan is aligned with NextGen R&D plan and builds upon plans developed by the DOD and the private sector to advance alternative aviation fuels and alternative energy.[36]

STATE OF THE ART

Energy Diversity

Interest in alternative aviation fuels derived from non-petroleum sources is growing. Alternative fuels may broadly be classified into two categories, "drop-in" and "non-drop-in" fuels. "Drop-in" fuels are those that can be substituted directly for conventional fuels without any changes to aircraft, engines or fuel delivery systems required. The U.S. commercial aviation supply chain established the Commercial Alternative Aviation Fuel Initiative (CAAFI) in October 2006.[37] CAAFI is best characterized as a process to generate data and communicate among and between aviation fuel supply chain sponsors. CAAFI coordinates the development and commercialization of "drop-in" alternative aviation fuels and is considering the feasibility, production, and environmental footprint—"well to wake"—of aviation fuels. CAAFI is also exploring the long-term potential of other fuel options. The goal is to ensure an affordable and stable supply of environmentally progressive aviation fuels that will enable continued growth of commercial aviation.

Presently, synthetic "drop-in" jet fuels can be manufactured from coal, natural gas or biomass (or blends) using the F-T process. There is currently no major U.S. source of these fuels, although there are plans for new refineries in various stages of development. In the future, synthetic jet fuel may come from oil shale, tar sands or other hydrocarbon feedstocks mixed with biomass. In the F-T process, the base feedstock is gasified and then recombined to form a synthetic fuel. Synthetic fuels are very similar in chemistry and

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[35] J. Waitz, J. Townsend, E. 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.

[36] D. L. Dagget, O. Hadaller, L. Maurice, M. Rumizen, N. Brown, R. Altman, and H. Aylesworth, "The Commercial Aviation Alternative Fuels Initiative," Society of Automotive Engineers Paper 2007-01-3866.

[37] Ibid.

performance to conventional jet fuel, but have very little sulfur, particulates, and aromatics, and have a slightly higher hydrogen-to-carbon ratio. This may result in much lower particulate exhaust emissions, and slightly lower CO_2 emissions at exhaust, although significant CO_2 emissions will occur with non-renewable feedstocks during the fuel synthesis process in the absence of sequestration. In addition, synthetic fuels exhibit excellent low-temperature properties, maintaining a low viscosity at cold ambient temperatures. High temperature properties are also improved, resulting in improved heat sink capabilities with less fuel system carbon deposits.

A blend of F-T and conventional jet fuel has already been in use for many years in the Johannesburg, South Africa airport; hence it is possible to supplement current jet fuel supplies with synthetic-derived fuel. Energy inputs and outputs throughout the production cycle must be considered in accordance with the CO_2 emissions produced and CO_2 mitigation strategies. For example, the additional CO_2 that is produced during the fuel synthesis process could potentially be captured and permanently sequestered in the fuel production process. In addition, a mixed biomass feedstock has the potential to significantly reduce CO_2 emissions from the gasification process. Section 526 of the 2007 Energy Independence and Security Act prohibits federal agencies from procuring synthetic fuels unless life-cycle greenhouse gas emissions are less than those for conventional petroleum sources.

Renewable fuels provide other options that could be “drop-in” or “non-drop-in.” Renewable fuels are typically made from biological sources, such as plants that can be grown year after year. The plant material is generally composed of oils extracted from the plant’s seeds, such as soybeans, canola, or palm. In addition, animal fats are being used to produce test quantities of jet fuel from oxygenated olefins. The properties of some renewable fuels fall outside conventional jet fuel specifications, in particular energy density in terms of both volume and weight. Through additional processing, such as transesterification or hydrotreating, these extracted materials may become more similar to diesel or jet fuels. Also, renewable fuels may be blended with other feedstocks to meet jet fuel specifications.

A drawback of renewable fuels is that, because of limited excess farmland availability, current grain-based and oil-seed based biofuels are not capable of supplying a large percentage of fuel without displacing food production.[38] However, future feedstocks with larger fuel yields per unit mass, such as algae, cellulosic biomass, and inedible oil seeds (e.g., jatropha) may improve supply capability. 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, which could lead to a more sustainable aviation fuel.

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[38] Ibid.

Diversifying the energy supply for airports and airbases includes connecting them to existing wholesale suppliers of alternative energy. This activity can benefit from leveraging work outside of aviation to develop sustainable or renewable energy sources, particularly electricity. For forward-deployed military airbases, local sources of alternative energy may need development to reduce logistical footprints.

Energy Efficiency

To ensure the long-term economic and environmental performance of air transportation, government, academia, and industry must continue to press forward with research, development, test, and evaluation aimed at affordably increasing aviation fuel efficiency. Efficiency gains can be found at the aircraft level, as well as at the airspace system level.

There are three ways to improve aircraft fuel efficiency: increasing aircraft lift-to-drag ratio, primarily by reducing drag; reducing engine specific fuel consumption; and reducing airframe and engine weight. For most of today's commercial aircraft, nearly all the fuel is used in cruise flight. An important measure of merit for energy efficiency in cruise flight is the lift-to-drag ratio. A higher lift-to-drag ratio also means better energy efficiency. For large subsonic transport aircraft, lift-to-drag ratios have hovered around 20 for decades. Today's aircraft turbine engines are typically designed to optimize fuel efficiency at a single operating condition such as cruise. Turbine engine fuel efficiency is generally achieved by increasing the overall pressure ratio of the engine; however, higher pressure ratios increase operating temperature, which could also increase the emissions of certain pollutants, particularly NO_x, unless there is also a change in combustor technology. New engine cycles under development may lead to enhanced energy efficiency without this penalty on emissions.

Other areas requiring emphasis include advanced aerodynamic design tools to achieve high pressure ratios, advanced lightweight, high-strength, high-temperature materials and structures, thermal management systems, variable-cycle turbine engines able to operate at multiple design points with greater thrust-to-weight ratios, revolutionary aircraft configurations with much higher lift-to-drag ratios that maintain laminar flow across the airfoil, greater use of composite materials, advanced structural designs that enable new aircraft configurations and reduce aircraft weight, and improved integration of airframe and engine.

One example of a revolutionary configuration that potentially offers a higher lift-to-drag ratio is that of the blended or hybrid wing body (BWB). Research is underway to target the challenges of reduced fuel consumption based upon a BWB aircraft design configuration. An 8% scale-model concept, the X-48B, does not have a tail; the wing itself blends into the fuselage, giving more lift and less drag. Its maiden flight in July 2007 was a first step at validating structural, aerodynamics, and operational advantages of such revolutionary designs. This concept may also provide benefits in noise reduction and lower emissions. Novel engine concepts such as the open rotor or unducted fan also have potential for significant reduction in fuel consumption, but trade-offs with noise must be carefully considered.

The development and integration of clean and quiet operational procedures will foster a more efficient NAS and reduce fuel use. For example, Continuous Descent Arrival (CDA) operational procedures are being transitioned and integrated into the NAS. CDA demonstrations have proven that optimal trajectory-based aircraft procedures offer significant efficiency improvements. Trials and demonstrations reinforce maturation of operational approaches, where appropriate. Efficiencies beyond terminal operations are also being pursued to include surface traffic movements and en route operations management. For example, under the Atlantic Interoperability Initiative for Reduced Emissions (AIRE) and the Asia and South Pacific Initiative to Reduce Emissions (ASPIRE) Programs, air traffic control system demonstrations are being launched to investigate these potential efficiency enhancements. Additional investments will further explore and demonstrate new capabilities. By 2025, coordinated decision-making through comprehensive automated systems communication/data networking of surface movement/en route/terminal domains will be vital for total "gate-to-gate" fuel efficiency.

Environmental Challenges

In tandem with the energy efficiency and supply challenges, there are environmental challenges generated by aviation, primarily involving aircraft noise and emissions. Protection of human health and the environment could impact the ability of the aviation system to continue to expand in order to meet national or international economic and mobility needs unless there are continued and increased environmental performance improvements. Airport expansion or new construction is often a contentious issue facing community resistance, and competes with demand for land in urban areas and protection of scarce natural and wild lands such as wetlands. Concerns over the climate impacts of aviation are also significant and could impede the growth of the worldwide air transport system.

Noise

The United States has made great strides in reducing aircraft noise. Since 1975, as air travel growth has gone from approximately 200 million to more than 700 million passengers per year, exposure to significant aircraft noise for communities around airports has declined more than 95%.[39] Most of this improvement has been driven by the introduction of the turbofan engine and promoted by new certification standards and a forced phase-out of 55% of the older, louder fleet as a result of the Airport Noise and Capacity Act of 1990.

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[39] J. Waitz, J. Townsend, E. 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.

Further technology gains resulting in significant noise reduction will be challenging. Although incremental technology improvements will result in moderate noise reduction, large reductions in noise are dependent on revolutionary concepts, particularly through integration of propulsion and airframe systems, which may require large capital costs and long lead times for development. For the N+2 generation of aircraft, the Silent Aircraft Initiative (SAI) has focused upon reducing noise at takeoff and landing while maintaining cruise performance by using a new engine and airframe design derived from a BWB concept. In addition, the NASA Fundamental Aeronautics research projects are identifying subsonic conceptual designs such as cruise-efficient short takeoff and landing (CESTOL), and advanced rotorcraft with acoustic performance characteristics that offer a relatively quiet approach to underutilized or unused airport ground and airspace infrastructure. However, there are still many technical challenges to overcome before these designs can become reality in the far term.

Emissions

The air quality impacts stemming from the contributions of aviation emissions are an increasing concern. Emissions of NO_x, carbon monoxide (CO), unburned hydrocarbons (UHC), some of which are classified as hazardous air pollutants (HAP), and PM are of concern in the vicinity of airports. NO_x, CO, and UHC emissions from aircraft and other ground-based sources lead to local and regional production of ozone in photochemical smog reactions. Jet fuel can contain up to 5000 parts per million sulfur (although the average is 700 ppm), which can lead to the formation of sulfur oxides and sulfates that can cause respiratory illnesses and aggravate cardiovascular disease, as well as cause acid rain and damage infrastructure.

Two areas of increasing importance and high uncertainty relating to air quality have emerged for aviation. The first is fine PM, and the second is the potential for aviation to emit HAP. There currently are no standardized test procedures or emission standards for PM from aircraft engines. The aircraft emissions measurement community is still working to define a measurement and sampling protocol for total PM emissions including the volatile and non-volatile fractions, and continued research is required to support these efforts. In some recent airport environmental assessments, HAP have figured prominently, and the need to characterize aircraft HAP emissions and impacts is critical to support timely environmental assessments. Piston-engine GA aircraft use aviation gasoline that contains lead and remain the only U.S. transportation mode that still uses lead as an additive to enhance octane. There is a NAAQS for lead, and further research is needed to develop an unleaded alternative aviation gasoline that has the performance characteristics of high-octane fuel.

Aviation emissions of CO_2, water vapor, NO_x, and PM in the upper troposphere and stratosphere are of concern because of their potential direct and indirect effects on Earth's climate.[40] There are many opportunities for technological and operational improvements to reduce emissions of CO_2, NO_x, UHC, CO, and PM. These options for reducing emissions present engineering, safety, and cost challenges that must be overcome before they can be implemented in the fleet. Research programs in the United States (NextGen and its Continuous Low Energy, Emissions and Noise [CLEEN] initiative) and Europe (European Air Traffic Management System known as SESAR and the Clean Sky initiative) are underway to address these challenges.

Historically, the most difficult pollutant to control for aviation has been NO_x. The contribution of aviation to NO_x emissions around airports is expected to grow. This growth is due to the tradeoff between engine efficiency and NO_x emissions performance in the engine combustor. Engine overall efficiency has been increasing from less than 20% in early turbojets to 30% in current high-bypass turbofans. Improvements in both propulsive and thermal efficiencies have contributed to these increases, and further improvements in both factors can be expected in the future. Higher pressures and temperatures in the combustor translate into higher NO_x production, assuming similar combustor technology is retained. While these trends have been typically observed, there is no single relationship between NO_x and CO_2 that holds for all engine types. As the temperatures and pressures in the combustors are increased to obtain better efficiency, emissions of NO_x are expected to increase. Lower emissions control technology (e.g., cleaner combustors), new engine cycles, and operational procedures must make up the difference to avoid increased pollutant emissions from aircraft. Indeed, the relatively wide range of NO_x emission rates in currently certified engines shows the potential for future improvement.

Climate Change

In addition to local and regional air quality, there is increasing concern in the United States about the potential impact of aviation emissions on global climate change. Scientific assessments also suggest that the resulting chemical and physical effects due to aviation are such that it may have a disproportionately large effect on climate per unit of fuel burned when compared to terrestrial sources.[41] The last major international coordinated effort to focus solely on assessing the contribution of aviation to greenhouse gases was published by the Intergovernmental Panel on Climate Change (IPCC) in 1999.[42] Aircraft have been estimated to contribute about 3.5% of the total radiative forcing (a measure of change in climate) by all human activities. This percentage, which excludes the effects of possible changes in cirrus clouds, is projected to grow.[43] The recently released Fourth Assessment Report by the IPCC[44] notes that aviation CO_2 emissions account for about 2% of global totals.[45] Due to

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[40] Intergovernmental Panel on Climate Change Special Report, "Aviation and the Global Atmosphere," 1999.

[41] Ibid.

[42] Ibid.

[43] Ibid.

[44] Intergovernmental Panel on Climate Change Fourth Assessment Report, "Working Group 1: The Physical Science Basis," 2007.

[45] Ibid.

new scientific knowledge and more recent data, estimates of the climate effects of contrails have been lowered. Aircraft in 2005 are now estimated to contribute about 3.0% of the total of the radiative forcing by all human activities, again excluding the possible effects of cirrus clouds. The IPCC Fourth Assessment Report noted that mitigation of CO_2 emissions from the aviation sector can come from improved fuel efficiency, which can be achieved through a variety of means including technology, operations, and air traffic management. However, such improvements are expected to only partially offset the growth of aviation emissions. Total mitigation potential in the sector would also need to account for non-CO_2 climate impacts of aviation emissions. In 1999, the IPCC projected that aviation may eventually (~2050) account for 5% of total greenhouse gas emissions.

Because of the uncertainty in understanding the scale of the indirect impacts of aviation on climate, appropriate technological, operational, and policy options for mitigation are also uncertain. While the United States has increased investment to reduce uncertainty in indirect climate change impacts, major U.S. research programs have generally not evaluated the unique impacts of aviation. There is a good understanding of the effect of aircraft-generated CO_2 on climate. However, there are large uncertainties in the present understanding of the magnitude of climate impacts due to aviation NO_x emissions and contrails. The impact of PM and its role in enhancing cirrus cloudiness are also uncertain. Metrics to assess the impact of these emissions and to determine their relative impact compared to CO_2 are needed. There is also need for enhanced scientific knowledge because often there are tradeoffs among emissions. For example, a more efficient engine that produces less CO_2 tends to produce more NO_x.

Water Quality

Water quality is a very important environmental issue. Concerns about water quality impacts currently limit several airport expansion projects. The effect of airport operations on water quality has been garnering attention, as regulators look beyond the more obvious sources of water pollution and attempt to address issues such as storm water runoff and other non-point sources (e.g., rainwater or snowmelt). Airports, which typically include large expanses of impervious surfaces and host activities that can generate discharges of potential contaminants, have been subject to the requirements of the Clean Water Act's regulations for over a decade. Implementation of these rules to the unique operating environment of airports is still being assessed. More recently, other water quality initiatives, such as the identification of impaired bodies of water and the efforts to set total maximum daily loads for specific pollutants for those bodies of water, have added complexity to environmental management of water impacted by aviation operations. Water quality issues warrant additional study and evaluation.

The relationship and occasional tension between protecting the environment and protecting the safety of the traveling public have arisen in the water quality context. For example, deicing and anti-icing agents may have environmental impacts beyond what is known today. Although airports are required to capture these agents for recycling or disposal, some questions have been raised about potential releases of air emissions from deicing agents. Water quality impacts caused by discharges of aircraft deicing fluids are of significant concern. Effects include oxygen depletion in water bodies, toxicity to aquatic species, and endocrine disruption. Runoff from pavement deicing also contains pollutants, but less is known about the extent of impacts and of effective technologies to mitigate such impacts. Near-term efforts focus on improving airport management of the waste products from aircraft deicing and continuation of research into the effects of pavement deicing on water quality.

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:[46]

1. 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.
2. 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.
3. Improvement is required in the capability to optimize aircraft noise, fuel efficiency, and emissions impacts using advanced technologies, operational procedures, and computer models.
4. 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 NO_x and PM, on climate; and the impact of PM and HAP 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.
5. 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 NO_x and contrails/cirrus clouds.

Table 6 depicts which energy and environmental challenges apply to the three energy and environmental R&D areas.

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[46] The challenges listed within this chapter of this Technical Appendix are listed according to their appearance in the Plan. No prioritization or ranking is implied or intended by the order of presentation within the Plan or this Technical Appendix.

Table 6. Mapping Energy and Environment Challenges to Research Areas

	Enable New Aviation Fuels Goal 1	Increase Energy Efficiency Goal 2	Decrease Environmental Impacts Goal 3
Challenge 1	x		x
Challenge 2	x	x	x
Challenge 3	x	x	x
Challenge 4	x	x	x
Challenge 5			x

Development of alternative aviation fuels and energy sources is critical to establishing an energy supply that is more diverse and environmentally friendly than those currently derived from petroleum. Aviation must have a reliable and cost effective energy supply, as well as effectively address environmental challenges related to energy production, aircraft noise, air quality, climate change, and water quality.

A more complete understanding of the complex interdependencies that exist between aircraft noise, emissions, and fuel burn is required for tackling each of these issues in a cost-beneficial manner. Sound approaches to policy-making require better understanding of the impacts and interdependencies of fuels, design, and operational choices, as well as understanding the use of a systems approach. In trying to assess overall efficiency, assess health and welfare impacts, optimize efficiencies and develop environmental mitigation strategies, it has become evident that there are potentially important tradeoffs and that an interdisciplinary approach is warranted. A successful integrated approach will better inform policy-makers, help maximize the benefits of proposed actions, guide research investments to optimize payoff, influence design practices, and inform the public about the potential impacts of proposed actions.

Improvements are needed in the capability to collectively optimize aircraft noise, fuel efficiency, and emissions impacts using advanced technologies, operational procedures, and computer models. For example, there is an increased recognition that a more complete understanding of the complex interdependencies that exist among aircraft noise, fuel burn, and emissions is required for designing and regulating aircraft. Efforts are underway to improve the capabilities to assess aviation noise, fuel burn, and emissions impacts, using advanced diagnostics and computer models. These efforts are enabling the ability to computationally assess how reducing one impact affects another, and how to devise the best balance of cost-beneficial solutions.

Scientific uncertainties must be reduced to reasonable levels that allow for sound decisions and appropriate action. Such uncertainties include: the overall life-cycle impacts of alternative aviation fuels, the climate impacts from aviation emissions such as NO_x and PM, and the impact of PM and HAP on surface 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. Embedded in the broader energy and environmental issues are several scientific uncertainties concerning aviation energy issues and aviation environmental impacts. There are uncertainties regarding development of enhanced metrics to characterize noise impacts, the impact from aviation emissions such as NO_x and PM on climate and air quality, and uncertainties derived from specific model formulation errors.

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 NO_x emissions, contrails, and cirrus clouds. There are key process uncertainties such as approaches to quantify aviation emissions and their global distribution. The need to evaluate public health risks associated with exposure to aviation emissions and the development of criteria on which to base such health assessments comprise additional knowledge gaps. Other types of uncertainty involve the coupling across different Earth atmospheric system components, and possible nonlinear responses to disturbances and/or feedbacks within the chemical systems of the atmosphere. Aircraft-induced cloudiness, which comprises contrail cirrus and modification of cirrus by aircraft exhaust soot emissions, is the most uncertain component in aviation climate impact assessments.[47] Additional research in these areas is essential.

Ensuring energy availability and protecting the environment will be critical elements in meeting military needs and allowing commercial capacity to expand. The United States has developed a strong and compelling vision under the JPDO NextGen plan for tackling environmental issues to ensure that aviation growth can be sustained. In addition, development of alternative aviation fuels and energy should be viewed as an opportunity to create sources that are more environmentally friendly than those currently used.

SUMMARY OF R&D ACTIVITIES SUPPORTING ENERGY AND ENVIRONMENT GOALS

Goal 1 – Enable new aviation fuels derived from diverse resources to ensure a secure and stable fuel supply

The DOD is pursuing an alternative fuels technology program to identify and enable use of a single, environmentally friendly fuel with composition and properties sufficient to serve

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[47] Climate Change 2007 – The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the IPCC (http://www.ipcc.ch/ipccreports/ar4-wg1.htm), 2007.

the needs of a multi-vehicle, multi-mission battle-space environment. This effort is focused on evaluating the properties of fuels, including energy density, high and low temperature properties, lubricity, and aromatics content, and the performance of fuels in military systems. The end result of this effort is to develop a knowledge base to inform a science-based certification process and streamline introduction of alternative fuels into military aviation systems. The near-term focus is on the certification of F-T fuels, with far-term efforts considering other sources, including biofuels and renewable sources.

The aviation-relevant part of the mission of the Department of Energy (DOE) is "to advance the national, economic, and energy security of the United States" and "to promote scientific and technological innovation in support of that mission." Several offices within the DOE support relevant R&D applicable to aviation energy and environment, including: the Office of Science, offices of Advanced Scientific Computing Research, Basic Energy Sciences, and Biological and Environmental Research; the Office of Energy Efficiency and Renewable Energy; and the Office of Fossil Energy. This R&D is conducted at universities and several DOE national laboratories. The research is often foundational in nature and applies across multiple science and technology goals. DOE is conducting aviation-relevant energy and alternative fuels R&D in biofuels derived from plants, microbes, and algae, efficient biofuel processing, alternative fuels combustion, and carbon capture and sequestration (for the development of alternative F-T fuels). DOE's scientific facilities, such as its leadership-class computing facilities, advanced bioprocessing facilities, and the Combustion Research Facility, give U.S. scientists, including other U.S. government entities, world-class research capabilities that can be applied to alternative fuels research.

The FAA is one of the sponsors of the CAAFI created in October 2006. CAAFI coordinates the development and commercialization of "drop-in" alternative aviation fuels. CAAFI participants are also exploring the long-term potential of other fuel options. In addition, the FAA is initiating a new program named CLEEN. The CLEEN program, in part, seeks to demonstrate alternative fuels for aviation to reduce emissions affecting local quality and greenhouse gas emissions, and increase energy supply security for NextGen.

The NASA Aeronautics Research Mission Directorate (ARMD) Fundamental Aeronautics Program performs long-term research focused on removing the environmental and performance barriers that may prevent the full realization of the projected growth in capacity of NextGen. In support of this, the Fundamental Aeronautics Program is pursuing the development of alternative fuels, with emphasis on addressing challenges related to use of alternative fuels in aircraft engines.

Goal 2 – Advance development of technologies and operations to enable significant increases in the energy efficiency of the aviation system

The DOD is pursuing advanced structural concepts to affordably improve the fuel efficiency of aircraft by reducing the weight and cost of aircraft structures, increasing the durability and safety of structures, and efficiently integrating mission systems functions with structures. The DOD is also developing technologies and aircraft configurations to dramatically improve aerodynamic efficiency and improve turbine engine performance. Turbine engine research includes efforts to improve the thermal efficiency of engines as well as variable-cycle technologies to optimize performance across the flight envelope. While R&D at the DOD is primarily focused on providing advanced military capability, many of these technologies may also provide benefits in terms of enabling reductions in fuel consumption through improved efficiency.

DOE is conducting aviation-relevant energy efficiency R&D in: leadership-class computing and algorithms for first-principle calculations (applicable to air-flow models, combustion, and catalysis), advanced materials science and chemistry; energy-efficiency technologies for industry, buildings, and transportation such as solid state lighting and advanced electrical energy storage and battery technologies; and conventional and alternative fuel combustion. DOE's scientific user facilities—including computational capabilities, and light and neutron scattering facilities for probing materials structure and properties—are open to government, academia, and industry for R&D in support of this goal.

The FAA's CLEEN program also seeks to demonstrate aircraft and engine technologies that enhance fuel efficiency. The goal is enabling a more efficient fleet that will operate with less energy usage. The FAA, together with international partners, is pursuing efforts aimed at enhancing energy efficiency and further reducing aviation's environmental impact (Goal 3). AIRE, a research venture between the FAA, the European Commission, and industry partners, will focus on upgrading air traffic control standards and procedures for trans-Atlantic flights. ASPIRE, a similar initiative by the FAA with the Asian-Pacific region, was also recently put in place. Both will enhance energy efficiency as well as reduce environmental impacts (Goal 3).

NASA's Fundamental Aeronautics Program is conducting R&D in revolutionary aircraft configurations, lighter and stronger materials, improved propulsion systems, and advanced concepts for high lift and drag reduction—all of which target the efficiency and environmental compatibility of future air vehicles. The Fundamental Aeronautics Program has four projects: SRW, SFW, Supersonics, and Hypersonics. The first three projects have significant R&D efforts to reduce aircraft fuel burn and increase energy efficiency. The SFW Project has aggressive goals to reduce aircraft fuel burn: by 33% for N+1, 40% for N+2, and more than 70% for N+3 aircraft.[48] The focus is on enabling technologies such as advanced aircraft configurations, flow control, adaptive and flexible wings, lightweight and multi-functional structures, highly loaded turbomachinery, advanced turbine cooling, and higher temperature materials. The project is also developing CESTOL aircraft that cruise at high speed with low environmental impact, yet can take off and land on very short runways.

The Supersonics Project is developing technologies for improving fuel efficiency by 15% for N+2 and 25% for N+3 aircraft, compared to N+1 baseline business jet configuration. One of the goals for the SRW Project is to increase the propulsive efficiency of conventional helicopters as well as tiltrotor configurations through the development of variable speed rotor systems, advanced materials, and oil-free turbomachinery systems. The project is developing technologies for advanced rotorcraft (e.g., large civil tiltrotors) with heavy lift and long range capability along with reduced environmental impact, which, in combination with the CESTOL aircraft developed in the SFW Project, is expected to play a key role in the metroplex system envisioned for NextGen.

One of the major focus areas of NASA's Fundamental Aeronautics Program is to improve predictive capability for aircraft performance (i.e., reduce uncertainty in prediction capability) and to develop physics-based MDAO tools to assess the trades between the three major objectives: (1) noise—airframe, engine, rotor noise generation and scattering, (2) emissions—propulsion systems and fuels, aircraft operations modes and dispersion, and (3) performance—airframe and engine efficiency. The MDAO capability is required to understand the design compromises that will lead to very quiet airplanes with low levels of emissions and significant performance improvements, as well as quieter rotorcraft with increased payload, range, and handling qualities.

The mission of the NSF is "to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense…" The NSF supports basic research in all the major areas of science and engineering mainly through investigator-initiated projects, and seeks to lay the foundation for the future through the support of basic research in diverse areas and several of those areas will affect aviation. A portion of the research supported by NSF is fundamentally related to energy and environment topics in aviation. For example, a current effort supports development of casting methods for combinations of lightweight metals such as aluminum and magnesium to replace iron and steel. Other relevant NSF research includes efforts to develop scalable portable thermal radiation algorithms for thermal radiation turbulence/chemistry interactions, and studies of the dynamics of ignition and extinction fronts on diffusion flame sheets, which can provide valuable insight into advanced combustor development.

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[48] The reference aircraft is a B737-800 with CFM56/7B engines, representative of 1998 entry into service technology; 70% is a 25-year stretch goal and assumes significant advances in novel configurations, engine performance, propulsion/airframe integration, and materials.

Goal 3 – Advance development of technologies and operations to decrease the environmental impact of the aviation system

DOE is conducting aviation-relevant environmental R&D in: leadership-class computing and algorithms for highly complex systems (combustion modeling and wing air flows); combustion research on alternative biofuels; climate modeling and climate science, particularly the contribution of aerosols and clouds; and sustainable biofuels development. Again, DOE's scientific user facilities are available for the broader science and technology community to utilize in support of this goal.

In anticipation of the emerging environmental issues associated with aircraft operations, the EPA's National Risk Management Research Laboratory started a small research program in 2003 to characterize the PM and HAP emissions from commercial aircraft turbine engines. This research was conducted in collaboration with a number of other governmental agencies, universities, airports, airlines, and engine manufacturers under the umbrella of NASA's Aircraft Particle Emissions eXperiment (APEX). Three test campaigns were conducted by the EPA as part of APEX at NASA's Dryden Flight Research Center, the Oakland International Airport, and NASA's Glenn Research Center. At present, emissions data are available for seven different commercial engine types. Although the campaigns collected a considerable amount of new data and improved understanding of aircraft engine generated emissions, the work also revealed a number of important questions requiring further research. Emphasis should be placed on: measurements at the engine exit plane under various modes of operation; characterization of particle size and composition at the exit plane and in the evolving plume; characterization of the dynamics of the evolving plume; and understanding the importance of ambient conditions and airport operations on aircraft emissions concentrations and properties.

The FAA is seeking to develop and validate methodologies, models, metrics, and tools to assess and mitigate the effect of aircraft noise and aviation emissions in a manner that balances the interrelationships between emissions and noise, and that considers economic consequences. It is also developing computer models and impact criteria for use by civil aviation authorities in assessing proposed actions. Researchers are also developing a better science-based understanding of the effects of aircraft noise and aviation emissions.

The FAA's CLEEN program also focuses on reducing current levels of aircraft noise, air quality, and greenhouse gas emissions. Its goal is to mature previously conceived noise, emissions, and fuel burn reduction technologies to levels that enable industry to expedite introduction of these technologies into current and future aircraft and engines. In addition, CLEEN seeks to assess the benefits and advance the development and introduction of alternative "drop-in" fuels for aviation, with particular focus on renewable options, which will reduce greenhouse gases throughout the "well-to-wake" life cycle. Accomplishment of the CLEEN goals will enable a more efficient fleet that will operate with less energy usage and permit expansion of airports in a manner consistent with the environmental goals of NextGen plans.

The FAA also conducts research on metrics and decision support tools for enabling NextGen Environmental Management Systems. Efforts are focused on developing a better understanding of the health and welfare impacts from aviation local air quality emissions and on translating impacts into improved metrics to construct Environmental Management Systems. In addition, this program provides sufficient knowledge toward establishing the uncertainty bounds of climate change effects of aviation to enable appropriate means to mitigate these effects. The research will accelerate achieving sufficient knowledge of the particulates and HAP effects of aviation to determine significant impacts, which is critical to capacity-enhancing projects.

The FAA also sponsors advanced noise and emissions reduction and validation modeling. The program is focused on developing operational procedures to enable reduction of aviation environmental impacts and establishing the benefits and costs for adopting these new procedures. In addition, the program focuses on establishing and advancing NAS infrastructure adaptation required to adopt CLEEN technologies and alternative fuels. Finally, the program will also develop and advance analytical tools to implement Environmental Management Systems to mitigate environmental impacts.

The FAA provides funding to the National Academy of Sciences' Transportation Research Board to support the Airport Cooperative Research Program (ACRP). The program is aimed at conducting research to support addressing airport issues, including environmental impacts. ACRP projects to date have included efforts targeted to address airport research needs on noise, local air quality, water quality, climate, and energy (including alternative fuels).

NASA's Fundamental Aeronautics Program is focusing on creating innovative solutions and technologies for addressing noise and emissions from aircraft. The SFW Project has set aggressive goals for reduction of noise and emissions. The noise goals are reductions of 42 dB (cumulative below stage 4) for N+2 and no transmission of noise beyond the airport boundary for N+3 aircraft. Research will include ultra high bypass engines, wing shielding of engines, drooped leading edges, continuous mold line flaps, active noise control, adaptive and flexible wing structures, and multifunctional structures with noise attenuation capability. The goals for NO_x reduction in the SFW Project are 60% for N+1, 75% for N+2, and more than 75% for N+3 aircraft. The Fundamental Aeronautics Supersonics Project has a goal to eliminate environmental and performance barriers that prevent practical supersonic vehicles. The focus is on enabling technologies to address cruise efficiency, sonic boom, and high altitude emissions. Research for noise reduction in supersonic aircraft includes low noise/high efficiency inlet nozzle design, sonic boom prediction, propagation, and mitigation, variable-cycle engine technology, and aero/propulsive/

servo/elastic behavior. Technologies for reduction of NO_x for both SFW and supersonic configurations include alternative combustor concepts, advanced fuel/air mixers, active combustion control, high-temperature combustor liners, and alternative fuels. The SRW Project is focused on improving the civilian potential of rotary wing vehicles while maintaining their unique benefits—the ability to take off and land vertically and to do so out of unprepared runways. Technologies are being developed to reduce noise and vibration through active and passive noise control techniques.

NASA's Airspace Systems Program is advancing the state of the art for air traffic management and operational procedures that will ensure that today's fleet and the new generation of vehicles can operate within NextGen in a manner minimizing aviation environmental impact. The program is focused on researching several operational improvement technologies, which include dynamic airspace configuration in the terminal area to enable fuel efficient arrivals and departures, CDAs with dynamic area partitioning, precision approaches to enable tighter lateral dispersion and close spacing between aircraft, advanced airport surface operation that would enable continuous taxi to takeoff, and optimized altitudes and arrival/departure routes. The program is also focused on conducting research studies to identify issues associated with deployment of new and advanced, environmentally friendly vehicles (being developed in the Fundamental Aeronautics Program) within NextGen.

As noted previously, some NSF research is fundamentally related to energy and environment topics in aviation. For example, a current effort supports development of nanomaterials that can be used on aircraft for anti-icing purposes. The successful development of such coatings has the potential to result in energy savings and in less environmental degradation due to deicing fluids. Another project supported by NSF focuses on optimization of airport construction sites, which could result in less habitat degradation. Two new programs at NSF offer support for research of importance to aeronautical concerns. Energy for Sustainability supports foundational research in renewable energy production, storage, and distribution, including fuel cells, hydrogen, and biofuels (also applicable to Goal 1). Environmental Sustainability supports projects to advance research in industrial ecology, green engineering, ecological engineering, and earth systems engineering. Atmospheric science research, which is supported by NSF, also provides increased understanding of consequences of various aviation scenarios, such as hydrogen-fueled aircraft on the radiative forcing function of climate. Currently, NSF supports basic research directly related to aviation with more than twice that invested in research indirectly related to renewable energy, climate change, and sustainability.

ANALYSIS OF OPPORTUNITIES WHERE ADDITIONAL R&D FOCUS MAY BE WARRANTED

The energy and environmental aeronautics R&D goals and objectives were assessed in light of the activities described in this Technical Appendix to identify areas of opportunity for potential increased emphasis as well as potential areas of unnecessary redundancy. The methodology for this assessment considered the previously described four key issues:

- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the near term;
- Whether the R&D activities ongoing or planned are sufficient to accomplish the objectives in the mid to far term;
- The level of coordination among executive departments and agencies; and
- The level of redundancy of efforts among executive departments and agencies.

Each of these four areas was given a broad assessment of green, yellow, or red based on this review. A green assessment denotes that R&D activities planned or ongoing are sufficient to achieve the objectives in the time frame indicated, that there is strong coordination among executive departments and agencies, and that there is no unnecessary redundancy. A yellow assessment indicates that R&D activities should provide significant progress toward the objectives but there is some risk due to fiscal or other constraints that merits continued attention, that coordination is taking place but could be improved, or that there does not appear to be unnecessary redundancy but additional coordination may be warranted. A red assessment highlights an area of concern, where additional emphasis or improved coordination among executive departments and agencies may be warranted to achieve the objective. The overall results of this analysis are shown in Table 7 at the end of this section.

As shown in Table 7, interagency coordination is very good for the energy and environmental R&D objectives. However, challenges were identified with the sufficiency of R&D planned relative to the ability to achieve many of the energy and environmental R&D objectives.

Goal 1 – Enable new aviation fuels derived from diverse resources to ensure a secure and stable fuel supply

DOD efforts to develop new alternative aviation fuels are making progress, but civil efforts, though making some progress, are not adequate to meet both the near- and the combined mid- and far-term objectives in a timely manner without either reconsidering the objectives or the current allocation of resources. However, the D&A plans are well coordinated, specifically through collaboration between the CAAFI and the DOD, and no unnecessary redundancies were identified. Near-term D&A plans include some foundational research and other R&D work necessary, such as that conducted in NASA's Fundamental Aeronautics Program, aimed toward achieving the mid- and far-term objectives.

Certification in a timely manner could help enable alternative fuels for the civil aviation sector. An area of opportunity identified for potential increased emphasis is R&D efforts appropriate to promote the development of private sector capabilities to produce alternative fuel (including renewable fuels) in the large quantities necessary to conduct tests essential for the certification process. These tests include evaluation of fuel specification and fit for purpose properties, turbine hot section tests, combustor rig tests, and engine and auxiliary power unit endurance tests.

Goal 2 – Advance development of technologies and operations to enable significant increases in the energy efficiency of the aviation system

Both near- and the combined mid- and far-term objectives are partially addressed by the individual D&A plans to develop technologies and operations leading to increases in the energy efficiency of the aviation system. As with Goal 1, the DOD is making progress toward energy efficiency objectives. While many of these efforts may have some applicability to civil aviation, they are primarily focused on military capability and efficiency of military aircraft. As such, focus is needed in R&D for civil aviation to meet energy efficiency objectives, but progress in the civil sector is such that efforts to fully address these objectives according to the envisioned timelines will require a reconsideration of either the objectives or the current allocation of resources.

The D&A R&D plans are well coordinated through the NextGen JPDO Environmental Working Group and no unnecessary redundancies were identified. The near-term D&A plans include foundational research and other R&D work focused on achieving the mid- and far-term objectives. However, it is important to emphasize that planned civil R&D activities are not adequate to achieve the civil subsonic aircraft fuel efficiency objectives of R&D Goal 2. A specific area of opportunity identified for potential increased emphasis was R&D aimed at increasing the fuel efficiency of civil subsonic aircraft.

The return on investment of these objectives may be substantial. By 2025, NextGen operational improvements developed under this goal, including air traffic management and aircraft technology, could reduce total fuel burned by 13% based on an analysis comparing 2025 traffic growth with no technology or operational improvements versus a 2025 high-density scenario assuming NextGen operational benefits, as enabled by the R&D in support of Goal 2. The scenario was conservative because it included only a subset of airports that represented only 70% of the commercial traffic. By 2025, NextGen high-density operational improvements could save more than 3.3 billion gallons of fuel per year. Assuming $4 per gallon fuel, savings of over $13 billion per year are possible. For example, the average flight in 2025 connecting Newark Liberty International Airport (EWR) with Los Angeles International Airport (LAX) would burn 19% less fuel, or about $5,000 per flight, with NextGen R&D investment compared to without the investment.[49] Increasing emphasis in the Goal 2 objectives to decrease risk for civil subsonic aircraft would have a very high payoff.

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[49] Over 80% of the benefit comes from new vehicle technologies. These technologies result in over 30% more efficient aircraft for new aircraft deployed after 2016. The remainder of the benefit comes from reduced delay and improved terminal area procedures.

Goal 3 – Advance development of technologies and operations to decrease the environmental impact of the aviation system

The individual D&A plans do not adequately address both the near- and the combined mid- and far-term objectives to develop technologies and operations leading to decreases in subsonic aircraft noise and aviation emissions that impact air quality and global climate. While progress toward these objectives is expected, continued focus will be needed to balance technical risk in these areas against timelines and fiscal restraints.

As with the R&D supporting the fuel efficiency goal, the D&A R&D plans are well coordinated through the NextGen JPDO Environmental Working Group and no unnecessary redundancies were identified. The near-term D&A plans include some foundational research and other R&D work focused on achieving the mid- and far-term objectives. As with investment in technologies and operations to enhance fuel efficiency, the return on investment to achieve the subsonic aircraft noise and emissions objectives may be substantial. In 2025, NextGen could reduce impacts on air quality by 20% to 40% across the pollutants based on an analysis comparing 2025 "No Action" versus 2025 NextGen high density, as described above. By 2025, NextGen could reduce the costs associated with air quality health risks by $1 to $3 billion. Considering greenhouse gases, NextGen could reduce socioeconomic damages associated with climate change by between $25 and $80 billion based on computations using the Aviation Environmental Portfolio Management Tool.[50] Increased emphasis on efforts to meet the subsonic aircraft noise and emissions objectives in order to decrease risk could also have a very high payoff. Another area of potentially high payoff is increasing emphasis on understanding the impacts of aviation emissions as delineated in the ACCRI. The initiative offers a robust, results-focused plan for decreasing uncertainties in understanding the impacts of NO_x and contrails/cirrus clouds on the climate to a level that informs cost-beneficial solutions. Planned NextGen investment in ACCRI partially advances the objective to reduce scientific uncertainties, but increased emphasis is needed across all D&A.

By current environmental impact measures, noise exposure is decreasing, but at the same time restrictions and community opposition are increasing. There is a need to better characterize human response to aircraft noise, including subjective (e.g., annoyance) and objective (e.g., health effects, sleep interruption, interference with learning) effects. The Federal Government has spent $7 billion between 1982 and 2007 in aircraft noise abatement actions and industry has invested billions in quieter subsonic aircraft. However, U.S. investment in research on human responses to aircraft noise has been limited, particularly during the past 10 years, and the expertise to conduct this research is virtually nonexistent in the United States. Addressing this capability gap is critical. An area of opportunity for potential increased emphasis is R&D aimed toward reducing subsonic fixed-wing aircraft noise emissions.

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[50] http://www.faa.gov/about/office_org/headquarters_offices/aep/models/.

Another area of opportunity identified for potential increased emphasis relates to the impact of aircraft operations on water quality. Individual D&A plans contain little to no R&D efforts to address the objectives to develop technologies and operations leading to decreased impacts on water quality. However, it is unclear whether such R&D efforts are needed until the near-term objective to determine significant water quality impacts of increased aircraft operations is met. Efforts through the Transportation Research Board-administered, FAA-funded ACRP are addressing this objective. An assessment of the adequacy of D&A plans should be revisited once the needs are identified.

Two remaining areas of opportunity identified for potential increased emphasis are for research to address the rotorcraft and supersonic aircraft noise objectives. Due to limited near-term foundational research, the state of noise reduction research on rotorcraft and supersonic aircraft is less advanced than for subsonic aircraft. The D&A plans have little unnecessary redundancy and are reasonably well coordinated. However, individual D&A plans are assessed to be insufficient to address these specific near- and combined mid- and far-term objectives with available resources.

This goal had the largest number of objectives identified as areas of opportunity for potential increased emphasis and they included efforts to better understand the impacts of and reduce noise and engine emissions from subsonic fixed-wing aircraft, rotorcraft, and supersonic aircraft; and reductions in the impact of aviation on water quality. However, a consideration of the potential returns on investment indicate that currently, the highest returns are expected from better understanding the impacts of and reducing noise and engine emissions from subsonic fixed-wing aircraft.

SUMMARY

In summary, the individual D&A plans taken together partially address the objectives to ensure energy availability and efficiency and protect the environment. However, these plans are largely insufficient to meet the objectives in a timely manner. The near-term D&A plans include foundational research and other R&D work aimed at achieving the mid- and far-term objectives, but risks associated with these objectives still remain. Continued attention will be needed to balance technical risk in these areas against available resources in order to ensure that energy and environment goals are achieved. A large number of areas of opportunity for potential increased emphasis were identified, but the areas where potential return on investment could be highest are the R&D efforts to advance alternative aviation fuels for civil aviation, increase subsonic civil aircraft fuel efficiency, and understand the impacts of and ways to reduce subsonic fixed-wing aircraft noise and engine emissions.

Table 7. Energy Availability and Efficiency Opportunities Analysis

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)	Near Term Objectives	Interagency Coordination	Redundancy	Mid and Far Term Objectives
Goal 1 Enable new aviation fuels derived from diverse resources to ensure a secure and stable fuel supply	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	R	G	G	R
	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”	Y	G	G	Y
Goal 2 Advance development of technologies and operation to enable significant increases in the energy efficiency of the aviation system	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 CESTOL 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 HSR program baseline (for details refer to Goal 5, Mobility section)	R	G	G	R
	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	Y	G	G	Y

Table 7. Energy Availability and Efficiency Opportunities Analysis—continued

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)	Near Term Objectives	Interagency Coordination	Redundancy	Mid and Far Term Objectives
Goal 3 Advance development of technologies and operations to decrease the environmental impact of the aviation system	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	Y	G	G	Y
	Develop improved tools and metrics to quantify and characterize aviation's environmental impact, uncertainties, and the tradeoffs and interdependencies among various impacts Enable quieter and cleaner N+1 aircraft and engines (32 dB cumulative below Stage 4)[c] and LTO[d] NO_x 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 HAP emissions and establish long-term goals for reducing to appropriate levels Enable N+2 aircraft and engines; (42 dB cumulative below Stage 4); LTO NO_x 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 NO_x Emissions reduction better than 80% below CAEP 2) Enable an order-of-magnitude reduction in high-altitude emissions for supersonic aircraft (reference HSR configuration)	R	G	G	R
	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 deicing fluids	Y	G	G	Y
	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	R	G	G	R
		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	R	G	G	R
	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	R	G	G	R

Notes:

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 and economic and 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.

ACRONYMS AND DEFINITIONS

4D	Four-dimensional
ACCRI	Aviation Climate Change Research Initiative
ACRP	Airport Cooperative Research Program
ADVENT	Adaptive Versatile Engine Technology
AIRE	Atlantic Interoperability Initiative to Reduce Emissions
ANSP	Air navigation service provider
APEX	Aircraft Particle Emissions Experiment
ARMD	Aeronautics Research Mission Directorate
ASIAS	Aviation Safety Information Analysis and Sharing
ASPIRE	Asia and South Pacific Initiative to Reduce Emissions
ASTS	Aeronautics Science and Technology Subcommittee
BWB	Blended wing body
C2ISR	Command, control, intelligence, surveillance, and reconnaissance
CAAFI	Commercial Alternative Aviation Fuel Initiative
CAEP	Committee on Aviation Environmental Protection
CAMI	Civil Aerospace Medical Institute
CDA	Continuous Descent Arrival
CESTOL	Cruise-efficient short takeoff and landing
CLEEN	Continuous Low Energy, Emissions and Noise (initiative)
CO	Carbon monoxide
CO_2	Carbon dioxide
COT	Committee on Technology
D&A	Department and agency
dB	Decibel
DEW	Directed energy weapons
DHS	Department of Homeland Security
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
EPA	Environmental Protection Agency
EPNdB	Effective Perceived Noise Level
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Controls
F-T	Fischer-Tropsch process
FY	Fiscal Year
GA	General aviation
HALE	High altitude, long endurance
HAP	Hazardous air pollutants

HSR	High Speed Research program
HTV	Hypersonic Technology Vehicle
HUMS	Health and usage monitoring system
INVENT	Integrated Vehicle Engine Technology
IRAC	Intelligent Resilient Aircraft Control
IVHM	Integrated Vehicle Health Management
JCAA	Joint Council on Aging Aircraft
JDAM	Joint Direct Attack Munitions
JPALS	Joint Precision Approach and Landing System
JPDO	Joint Planning and Development Office
LAX	Los Angeles International Airport
LTO	Landing and Takeoff Cycle
MANPADS	Man-Portable Air Defense Systems
MDAO	Multidisciplinary analysis and optimization
MW	Megawatt
NAAQS	National Ambient Air Quality Standards
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NDE	Nondestructive evaluation
NextGen	Next Generation Air Transportation System
NOAA	National Oceanic and Atmospheric Administration
NO_x	Nitrogen oxide
NSF	National Science Foundation
NS&HD	National Security and Homeland Defense
NSTC	National Science and Technology Council
NTSB	National Transportation Safety Board
OSTP	Office of Science and Technology Policy
PLdB	Perceived level of noise
PM	Particulate matter
ppm	Parts per million
R&D	Research and development
RDT&E	Research, development, test and engineering
RNP	Required navigation performance
SAI	Silent Aircraft Initiative
SFW	Subsonic Fixed Wing
SHM	Structural health monitoring
SRW	Subsonic Rotary Wing
STOL	Short takeoff and landing
TCAS	Traffic Alert and Collision Avoidance System
UAS	Uncrewed aircraft systems
UHC	Unburned hydrocarbons

Plan prepared by

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL (NSTC)
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