

i. THE NASA AERONAUTICS BLUEPRINT – A TECHNOLOGY VISION FOR AVIATION

This Blueprint for Aeronautics is a product of the National Aeronautics and Space Administration (NASA). It primarily addresses the challenges that confronted aviation in the United States before the terrorist attacks of September 11, 2001. Safety and security have taken on a whole new perspective since that event, and technology solutions are presented in this Aeronautics Blueprint. We also recognize that the issues that were facing air travel prior to September 11 will return and require innovative technology solutions.

The Blueprint addresses how new technologies can be brought to bear on these issues. Most interesting is the finding that these technologies can do more than resolve existing issues; they have the potential to open a whole new era in aviation and provide new opportunities in air transportation safety and efficiency, national defense, economic growth, and quality of life.

The National Aeronautics and Space Act of 1958 directs that Government-sponsored aeronautical activities be conducted to contribute materially to specific objectives, including the following:

- improvement of the usefulness, performance, speed, safety, and efficiency of aeronautical . . . vehicles;
- long-range studies of . . . the problems involved in the utilization of aeronautical . . . activities for peaceful . . . purposes; and
- preservation of the role of the United States as a leader in aeronautical . . . technology.

In executing this charter, NASA must work closely and partner with the Department of Defense (DoD), the Department of Transportation (DOT), the Federal Aviation Administration (FAA), academia, and industry to ensure that the research that NASA pursues finds its way into useful and timely products and processes.

Many of these stakeholders in areas of aeronautics and aviation were invited to offer their perspectives at various points throughout the preparation of this Blueprint—and they did so in a very significant way. One of the foremost recommendations in terms of next steps is to establish a more fully coordinated national strategy.

It is clear from our discussions that a consensus exists on the issues that need to be addressed, and there is agreement that technology is a significant component of the solutions. The Aeronautics Blueprint describes these issues and puts forth a vision of the technology advances that will change aviation. It does so with the understanding that the combined efforts of NASA, DoD, DOT, the FAA, academia, and industry will be needed to realize the vision. Action is needed to galvanize the intellectual and organizational resources of these bodies and to set overall goals and priorities. Failure to act risks significant economic and social consequences.

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iii. EXECUTIVE SUMMARY

Over the last century, aviation has evolved to become an integral part of our economy, a cornerstone of our national defense, and an essential component of our way of life. Aviation generates more than \$1 trillion of economic activity in the United States every year. Military aviation forms the backbone of the U.S. security strategy. All military services (Air Force, Navy, Army, and Marine Corps) possess aviation capability, and nearly a third of the Defense Department's budget relates to aviation activities. Americans per capita use aviation more than any other country in the world. Today personal travel accounts for more than 50 percent of commercial air transportation, and the percentage of people who have flown increases at an average of 2 percent per year.

As the Nation and the world become more dependent on the ability to move goods and people faster and more efficiently by air, important and difficult challenges have emerged. Saturation of the civilian air transportation system is causing delays and disruptions in air service. Military challenges have become more complex. The fight against international terrorism has replaced the Cold War. As a result, our military strategy has shifted from the

traditional "threat-based" defense planning of the past to a "capabilities-based" model in the future. The terrorist attacks of September 11, 2001, shocked the Nation by showing how terrorists used commercial aircraft as weapons of massive destruction. There is a need to reestablish the public's trust in aviation security and safety.

Advances in technology have paced aviation's evolution throughout its first century. Human investment and ingenuity, once the only bounds to growth in aviation, have produced a highly complex, integrated, and regulated aviation system. To move aviation ahead in the next century, we will need to capitalize on the convergence of a broad front of multidisciplinary advances in technology. Advances in information technologies are already enabling major changes in aviation. Aviation materials have improved dramatically over the last century; the coming revolution in nanotechnologies promises to accelerate that progress. Likewise, biological sciences are providing a new way to look at machines. Mimicking nature will enhance flight safety and result in more reliable air vehicles.

The Aeronautics Blueprint provided in this document describes a vision of the technology advances that will change aviation. It does so with the understanding that the combined efforts of NASA, DoD, DOT, the FAA, academia, and industry will be needed to realize the vision. The technology advances discussed will help solve today's challenges and will create a new level of performance and capability in aviation. They are targeted to produce

- advanced concepts for the Airspace System,
- revolutionary vehicles with significantly greater performance,
- a new paradigm for aviation security and safety, and
- assured development of the capable workforce for the future.

U.S. competitors are targeting aviation leadership as a stated strategic goal. If we fail to act now, we face the very real prospects of near-term gridlock, constrained mobility, unrealized economic growth, and the continued erosion of U.S. aviation leadership.

1.0 THE IMPERATIVE

1.1 AVIATION IS CRITICAL TO THE UNITED STATES

Vital to the Nation's Economy

Aviation generates more than \$1 trillion of economic activity in the United States every year. The aviation industry accounts for approximately 6 percent of the U.S. Gross Domestic Product. For many years, aviation products have provided the largest positive balance of trade across the entire manufacturing sector—\$26.7 billion in 2000. In fact, the total global market for aviation-related products and services over the next 20 years is expected to exceed \$1.3 trillion.

U.S. aviation transported 21.1 billion ton-miles of freight cargo in 2000. Over 40 percent of the value of international trade is moved by air. Revenue passenger miles flown in 2000 equaled 693 billion. To make this happen, the aviation industry employed about 10.9 million workers, with 800,000 in highly skilled jobs, representing \$278 billion in wages—a tremendous economic input.

By 2020, it is estimated that commercial air travel could exceed the volume of all auto travel in 1990. The expected rate of growth for airfreight is 1 percent higher than that of passenger travel for the near future. By 2018, the freight fleet is

expected to grow by more than 3,000 aircraft, contributing to the sale of over 15,000 commercial transports over this period, exceeding \$1.3 trillion of value. These estimates underscore the fact that civilian aviation is expected to continue to play an increasing role in the national and world economies.

Backbone of National Security

U.S. military aviation is a key element in our national defense strategy. Our ability to project power swiftly, precisely, and globally provides strategic tactical influence.

Military aviation forms the backbone of the U.S. security strategy. All services (Air Force, Navy, Army, and Marine Corps) possess aviation capability, and nearly a third of the Defense Department's budget relates to aviation activities. Over 46,000 aircraft, including fighters (air superiority), transports (strategic mobility), helicopters (tactical mobility), and unpiloted air vehicles (surveillance, reconnaissance, and strike), conduct hundreds of operations globally every day.

Part of the American Way of Life

The essence of America's freedom of movement hinges on aviation. Americans per capita use aviation more than any other country in the world. Today personal travel accounts for more than 50 percent of air transportation, and the percentage of people who have flown increases at an average of 2 percent per year. The number of domestic commercial travelers is expected to double in 10 years and triple in 20 years—to 1.8 billion passenger miles. Aviation serves 60 percent of all trips over 1,000 miles. Without question, aviation no longer is a luxury; it is an integral part of America's life.

1.2 KEY AVIATION CHALLENGES

Capacity

Today's aviation system is showing unmistakable signs of gridlock. Most air travelers have experienced congested airports, flight delays, and unreliable service. Since deregulation of the airline industry in the United States, air travel has tripled while the air transportation support infrastructure has remained relatively unchanged. Only one large hub airport and seven new runways have been opened in the past decade, while the number of departures has grown nearly 30 percent from 7 million to 9 million per year.

Economic forecasts predict that domestic air traffic volume will triple over the next couple of decades. Increasing delays may cripple such growth. Delays already have a serious impact on the U.S. aviation economy. For example, the estimated total cost of delays in 2000 alone was nearly \$6 billion. Perhaps more important, the growth in delays has outpaced the growth in air traffic. In the past three years, departures were up a modest 11 percent, while delays rose an astounding 127 percent. This points to the fact that air traffic is truly approaching gridlock and that our existing airspace management

system is incapable of accommodating this projected growth. Constraining air traffic growth will have damaging economic implications and corresponding serious consequences on our American way of life.

Noise and Emissions

The environmental issues related to aviation have resulted in restrictions imposed on aircraft and airport operations. Airport noise concerns are an increasing source of constraints on flight operations at many airports worldwide. Community noise restrictions limit hours and number of operations at all but the most remote airports. Sixty-two percent of all airports consider noise a serious problem, while 50 of the largest airports view it as their biggest concern. Noise concerns are also among the major hurdles confronting aviation infrastructure improvements such as airport expansion and construction plans.

Aircraft and airport emissions have a quantifiable effect on both the global and local environments. Local air quality regulations already have constrained operations at several U.S. airports and prevented the basing of specific military

aircraft within certain areas of the country. Furthermore, future efforts to address global warming concerns could lead to limitations on the number and type of aircraft flight operations. If the issues of noise and emissions remain unresolved, the air transportation system of the future is likely to be highly constrained with a major shortfall in capacity and a serious degradation in accessibility.

Security and Safety

The safety and security of air transportation are paramount concerns for all Americans, and travelers rightly hold the aviation community to extremely high standards in this regard. Any incident receives visibility, and some are deemed a national tragedy. Each affects the public's faith and confidence in aviation as a whole. Although normal operations of the past two years have been very safe, it is too early to call this a trend. More important, recent tragic events pertaining to the security of the aviation system also will have a major effect on overall air transportation perception. Aviation safety and security will continue to be challenged in unforeseen ways that require constant vigilance.

1.2 KEY AVIATION CHALLENGES (CONTINUED)

Military Challenges

The U.S. national defense strategy demands that its most critical component, military aviation, be the most capable and technologically advanced in the world. Specifically, it must be capable of projecting power swiftly, precisely, and globally. This becomes strategically important as the United States continues to reduce its basing of forces around the globe. At the same time, the military is driving toward a more rapid and earlier response to thwart impending crises worldwide before they explode. Likewise, new and emerging threats have arisen that challenge current aviation capabilities and beg for innovative operational concepts complemented with new technologies.

Military aviation operations span the gamut of the air medium—from small hover aircraft to large hypersonic vehicles—from piloted high-speed transport aircraft to unpiloted agile strike vehicles. As the needs of military operations dynamically evolve, so too must previously untapped aviation technologies be developed.

Declining R&D

The strength of the Nation's academic, scientific, and applied research is a fundamental indicator of future technological capability and performance. Technologies that were initiated 15 years ago are just now being incorporated into civil and military aviation products. However, both U.S. industry and Government spending on aeronautics research and development has declined. Aerospace research and development funding has fallen by more than 50 percent from a 25-year peak in 1987. Industry has reduced research to 3 percent of sales, down from 5.5 percent just 2 years ago. Aeronautics infrastructure also has suffered. As an example, a major U.S. military development program has turned to foreign sources for wind tunnel testing because of better performance capabilities and cost effectiveness.

At the same time, the U.S. aerospace workforce shows serious signs of erosion. The skilled aeronautics workforce is aging and retiring, and new skilled workers are not choosing the field. The average age of workers employed in the aerospace industry is 47 and climbing

fast. U.S. graduates at the bachelor's and master's degree levels in aerospace engineering and related disciplines have dropped by 57 percent and 39 percent respectively. Overall, reductions in aeronautics research and technology may ultimately have irreversible consequences if the United States cedes to foreign competitors the leadership position we have held for the last half of the 20th century.

Leadership

The U.S. has been the recognized leader of the global aviation market since the end of World War II. Unfortunately, our global market dominance is rapidly declining, as evidenced by the drop in U.S.-produced civil transport aircraft. The European Airbus has made dramatic gains, capturing over 50 percent of the commercial market and displacing U.S. manufacturers, who previously enjoyed a market share in excess of 80 percent a little more than a decade ago. The Europeans are aggressive in seeking to overtake the U.S. leadership position and have a publicly stated a goal of establishing their global leadership in aeronautics by the year 2020 or sooner.

1.3 ROLE OF GOVERNMENT IN AERONAUTICS RESEARCH

The U.S. Government has played a major role in the development of aeronautics and aviation. Military interest started with the War Department's sponsorship of Samuel Langley's efforts to develop a heavier-than-air flying machine in 1898. Anticipating yet-to-be-proven civilian applications, Congress stimulated early commercial aviation by using mail delivery as a tool in the 1920s and 1930s.

Since then a highly complex, integrated, and regulated aviation system has evolved. The system involves governments at the Federal, State, and local levels. Commercial demand for aviation services has grown beyond system capacity. The number of industrial participants has increased, as has the diversity of their interests. Likewise, the role of foreign governing bodies has become more important and more influential.

Today, as the Nation and the world become more dependent on the ability to move goods and people faster and more efficiently by air, important and difficult challenges have emerged. Saturation of the civilian air transportation system is causing delays and disruptions in air service. The existing aviation infrastructure is not adequate to deal with

the demand for air travel and threatens to constrain future economic growth. Much of the air space management infrastructure owned and operated by the Government is aging and decisions need to be made about which facilities are upgraded, replaced, or closed. Furthermore, legitimate concerns about environmental issues such as noise and emissions constrain the physical expansion of much of that infrastructure.

Based on the Government's responsibility in the operation of the air traffic system and in providing for national security, it must be concerned about defining the solution path. Many issues such as the environment are external to the marketplace and are not typical issues in which the private sector can lead. Technology has and still can be a major component of the solutions. Based on its role, the government must be a player in establishing priorities, pursuing technology risk reduction efforts, and deploying certain new capabilities.

Historically, our society has benefited greatly from advances in aviation. The return to the country from aeronautical research and technology (R&T) has far exceeded the investment. This was the expectation of Congress when it first

sought to stimulate commercial aviation early in the 20th century. Since then, aviation has proven to be a major source of our economic and military strength.

Military challenges have become more complex. The Cold War has been replaced by the fight against international terrorism. As a result, our military strategy has shifted from the traditional "threat-based" defense planning of the past to a "capabilities-based" model. Our military must be prepared to deal decisively with hot spots anywhere in the world. As forward basing of U.S. military assets declines, rapid deployment of forces gains importance. The use of unpiloted air vehicles for surveillance, intelligence gathering, communications, and combat is becoming a major part of this changing strategy. These changes, in particular in aviation, were enabled because of the Government's investment in technology.

Aviation is still changing our society, and our society is changing its demands on aviation. Future changes promise to be as significant as changes of the past. The need for a continuing Government role in aeronautical R&T in support of civilian and military objectives is as strong today as it has ever been.

1.4 ONGOING NASA/DoD COLLABORATION

NASA has a long history of collaboration with the DoD, that includes all branches of services.

"NASA's support of specific military aircraft development programs and its fundamental research have provided many benefits to the DoD. By virtue of its independent agency perspective, NASA's assessments of evolving technology and aircraft systems have provided, and continue to provide, the DoD unbiased analyses, opinions, data, and extremely valuable recommendations for decisions about technology issues in its aircraft programs. NASA has been frequently called upon to participate or represent the DoD in early assessments and selections of competing aircraft designs. In addition, NASA's unique wind tunnels, simulators, and computational facilities have been extensively utilized for evaluations and development of military aircraft. The DoD benefits from the extensive experiences and corporate knowledge of the NASA staff as a result of NASA's participation in a vast number of aircraft development programs."¹

The reference provides specific examples and details the contributions of NASA research centers over the years in support of military aviation.

Looking toward the future, the DoD Joint Vision 2020 study describes the transformation of America's Armed Forces. "In 2020, the nation will face a wide range of interests, opportunities, and challenges, and will require a military that can win wars and contribute to peace."² The DoD Quadrennial Defense Review Report³ further underscores the dynamic environment in which the military and the American public may have to confront faceless weapons of terror. The report describes a shift from the traditional "threat-based" defense planning of the past to a "capabilities-based" model in the future.

NASA and DoD are collaborating on several research topics. One very significant issue for the safety of both civil and military aviation is the flightworthiness of aging aircraft. Other topics include advanced propulsion technologies, lightweight high-strength adaptable structures, adaptive controls, advanced vehicle designs, and new

collaborative design and development tools.

A full spectrum of vehicle types including subsonic and supersonic aircraft, sensing vehicles, extremely short take-off and landing airplanes, and uninhabited air vehicles are also addressed in these collaborations. From these interactions and joint planning activities came a consensus regarding a common set of civil and military goals for NASA and DoD to jointly pursue.

¹ Joseph R. Chambers, *Partners in Freedom*, NASA SP-2000-4519, 2000.

² Joint Vision 2020 Study, Director for Strategic Plans & Policy, Washington, DC, June 2000.

³ Quadrennial Defense Review Report, DoD, September 30, 2001.

1.5 ONGOING NASA/FAA COLLABORATION

In 1968, the Senate Committee on Aeronautical and Space Sciences recommended that NASA and the newly formed Department of Transportation undertake a joint study to evaluate the problems facing civil aviation and the potential benefits that might accrue from Government support of Research and Development in those areas. The ensuing DOT/NASA Civil Aviation Research and Development Policy Study recommended that the Federal Government should take an active role in developing a national aviation policy and conducting R&D to benefit civil aviation.

The top two concerns at the time were aircraft noise and congestion in the terminal, or airport, area. Thus began the current era of collaboration between NASA and the FAA. In 1992, the National Research Council's Aeronautics and Space Engineering Board reaffirmed the national need for such collaboration in its report "Aeronautical Technologies for the Twenty-First Century." The board recommended that NASA work with the aircraft manufacturers, the airline industry, and the FAA to bring about major improvements in the utility and safety of the global Air Traffic

Management system. The FAA/NASA relationship received further definition in 1995 through a Memorandum of Understanding cosigned by the FAA and NASA administrators. A formal partnership was established. Annually the two agencies produce a report that identifies for the community the specific research and development activities funded by each of the agencies and the proposed implementation plans for the resulting products. All research efforts are considered, including those sponsored by the agencies and performed by industry.

Current collaborative efforts are centered on the FAA's Operational Evolution Plan (OEP). The OEP is FAA's commitment to meet the air transportation needs of the United States for the next 10 years, with a focus on maintaining safety, increasing capacity, and managing delays. The FAA and NASA have worked to ensure that NASA's research program will support the plan and that the research program will continue to provide the FAA and industry with the long-term research needed to guide the evolution of the plan.

The OEP defines four capacity-demand problem areas: arrival/departure rate, en

route congestion, airport weather conditions, and en route severe weather. NASA-developed technologies are prominent in all four of these problem areas. Many of NASA's initiatives that were part of the FAA's Free Flight Program have been adopted and are being implemented under the OEP.

As a major FAA research partner, NASA has planned a follow-on program, the Aviation System Technology Advanced Research (AvSTAR). This program will build on existing research and technology development to help provide future additional operational capabilities. The AvSTAR initiative will begin with development of a Virtual Airspace Modeling System. This system will enable development of virtual airspace models and simulations that can be robust and have high fidelity enabling a clear understanding of the tradeoffs in various architectural approaches.

Working with the FAA and the broader community, the AvSTAR program will proceed to define advanced core component technologies to meet the air transportation requirements of the 21st century.

1.6 THE NASA ROLE

The National Aeronautics and Space Act of 1958 addresses the value of Aeronautics to the Nation: “The Congress declares that the general welfare and security of the United States require that adequate provision be made for aeronautical . . . activities.” The act more specifically defines the NASA role: “The improvement of the usefulness, performance, speed, safety, and efficiency of aeronautical . . . vehicles.”

In exchange for the receipt of “adequate provisions,” NASA’s efforts must go beyond the laboratory. The efforts must result in practical applications that will positively influence economic growth and opportunity. NASA’s efforts need to contribute to the strengthening of our national defense and they must enhance the overall quality of life in our highly mobile American society.

To accomplish this broader objective, NASA has established close

partnerships with the Department of Defense and its many services, the Department of Transportation, the Federal Aviation Administration, academia, and industry. These two-way partnerships provide to NASA the insight and understanding essential for establishing NASA’s long-term goals and research programs. In return, these partnerships facilitate the adoption of NASA-developed technologies and solutions by aviation product developers and process owners.

The unique expertise and facilities NASA uses to pursue its research objectives are national assets that have been called on to address near-term applications in aviation in times of great national need. NASA and its predecessor agency, NACA, have provided quick reaction support to the military and civilian sectors of aviation in the public good. During World War II, NACA put aside much of its research program in favor of working to improve the performance of our

military fleet of aircraft. More recently, as military aircraft started to maneuver in aerodynamic regimes previously uncharted, NASA worked with the Navy and Air Force to develop flight procedures and configuration modifications to enable safe, unprecedented flight controls and maneuvering capabilities. Similarly, in support of civil aviation, as the Nation’s airspace has filled to near saturation, NASA has collaborated with the FAA to develop near-term enhancements to air traffic control procedures in order to increase capacity without compromising safety.

This NASA role of strategic forward-looking breakthrough research combined with tactical problem resolution in response to priorities established through close partnerships has made many high-value contributions to our American society.

1.7 FIRST CENTURY OF AVIATION PROGRESS

Advances in technology change society in very predictable ways. First is a period of learning and experimentation during which the impact to society is small. Next, practical applications surface and societal changes take place at an accelerating pace. Last, as the technologies mature and become inherent parts of the society, the rate of change declines and seeks a limit. The three periods are often combined and represented by the characteristic “S-curve” shown in the facing chart.

Frequently, change results from the convergence of several technological advancements. Advances in aviation provide good examples of this pattern and are described as two “S-curves” spanning the first century of flight.

The Wright brothers initiated the first era in aviation in 1903. Their breakthrough flight not only depended on their technical innovations, including their pioneering efforts in lateral flight controls; it also capitalized on the growing understanding of fundamental aerodynamics and the newly developed internal combustion gasoline engine. Combining all of these advances was necessary for the Wright brothers to achieve the world’s first

powered flight. However, this dramatic event had little immediate impact on society at large and is represented by the lower portion of the first “S-curve.”

Aviation’s first significant impact on society was in its military application in World War I. Further advances in structures (riveted aluminum monocoque construction), aerodynamics (single wing with elliptical planform and retractable gear), propulsion (high-performance turbo-charged engine with variable pitch propeller), and navigation (inertial navigation) were necessary before aviation achieved practical commercial use in the early 1930s. Quickly, aviation changed society’s perception of distance and forever changed the face of military conflict.

Through the 1940s and 1950s, commercial aviation service grew rapidly and society adopted the propeller-driven airplane as a symbol of progress.

Like in the first era, the early benefits of the second era of aviation were military. Near the end of World War II, first Germany, then Britain developed the jet engine. The Germans employed this new propulsion technology as a brute-force upgrade to fighter aircraft, but it had no

measurable impact on the outcome of the war. Jet engines of that epoch lacked the efficiency to be applied to commercial aviation. This is marked by the lower portion of the second “S-curve.” Further refinements in jet engine technology (axial compressor), combined with new aerodynamic principles (swept wings), enabled the development of the KC-135. Its commercial twin, the Boeing 707, and the Douglas DC-8 set off a rapid conversion of commercial aviation to the jet age in the 1960s.

The application of new technologies (high bypass ratio turbofan, supercritical airfoils, fly by wire) and new approaches to the problem of air traffic control (radio navigation, radar tracking with onboard transponders) allowed the societal impact of the jet age to be truly global and extend far down the economic ladder. As the jet age has become an integral part of our society, the technology improvements in aviation have become incremental rather than revolutionary. Severe limits have been reached with regard to capacity and the environment.

As we move into the 21st century, the time is now to launch a new aviation era.

1.8 AVIATION'S FUTURE IS DRIVEN BY TECHNOLOGY

The NASA Aeronautics Blueprint lays out a technology vision for the next era in aviation. This technology vision must be implemented as part of a broad national plan that involves research organizations, such as NASA and academia, as well as the organizations responsible for applying the research products, such as DoD, DOT, the FAA, and industry.

The solutions resulting from the application of this blueprint will not only address the crises that exist today; they will go far beyond and enable a bold new era in aviation. This third aviation era has the potential to unleash new capabilities that will dwarf accomplishments of the past.

Even more than the previous eras, this new era will capitalize on the convergence of a broad front of multidisciplinary advances in technology. Understanding and applying these varied multidisciplinary advances will require interdisciplinary skills that are uncommon today. New education and training initiatives must accompany the technical research programs to provide a workforce with sufficient numbers that can address

the breadth of the technologies being developed.

The accelerating pace of technology advances worldwide introduces an element of urgency. If the United States is committed to maintaining its historical leadership in aeronautics, we must act now.

2.0 A BOLD NEW ERA IS POSSIBLE

2.1 A BOLD NEW ERA OF AVIATION IS POSSIBLE

Advances in evolving technologies have the potential to change aviation in a way that will dwarf achievements of the past.

Imagine having on-demand as well as scheduled air mobility, not just to hundreds, but to thousands of communities throughout the Nation and the world; traveling where we want, when we want, faster, safer, and with far fewer delays; having access to rural areas, no matter how remote; and having direct access to urban centers, no matter how congested.

Imagine the ability to provide same-day delivery of personal packages from any place of business to any address.

Imagine projecting our military might from bases in the United States to hot spots anywhere on the globe on the same day on which conflicts arise and deploying surveillance devices to provide local and regional intelligence instantly and continuously.

Imagine air vehicles that pass overhead quietly with no emission of objectionable gases into our atmosphere.

Imagine economic opportunity unconstrained by the infrastructure of highways and airports inherited from the last century, and fierce competition among entrepreneurs large and small, local and global, to provide innovations in air transportation services.

Imagine a future in which every traveling American has the opportunity to make choices regarding timing, destination, routes, and carriers, and the opportunity to choose to own, lease, or hire choices that today are reserved only for the rich.

Such a future is indeed possible. A spectrum of technologies awaits development to enable this future. Each technology will provide a different set of challenges, and each will mature at a different pace; all will contribute to the strengthening of our national security, an increase in economic opportunity, and the improvement of our overall quality of life.

2.2 ORGANIZATION OF THE AERONAUTICS BLUEPRINT

To serve as a catalyst in this new aviation era, NASA proposes a focused technology strategy that addresses the critical challenges in today's aviation system. NASA serves a unique and necessary role for the Nation as we move to reality what was once thought to be aviation fantasy.

NASA will provide leadership in innovative aviation technology solutions and concepts that will be the foundations for initiatives pursued by the Departments of Defense and Transportation, as well as industry.

As a technology provider in aeronautics, NASA can develop the research strategy the Nation needs to stimulate initiatives and assist their progress to maturity and payoff in terms of economic growth and national security thus leading to an improved quality of life for all Americans.

In this Blueprint, we present the specific challenges and the technology solutions NASA proposes to pursue. The Blueprint is organized into four primary focus areas:

- The Airspace System,
- Revolutionary Vehicles,
- Aviation Security and Safety.
- State of the Art Educated Workforce, and

In each area, we describe how the Blueprint will contribute to the vision previously described.

2.3 A COLLABORATIVE STRATEGY BASED ON SYSTEMS ANALYSIS

The aviation system is a system of systems. It is complex and highly integrated, involving some of the most advanced technologies produced by our contemporary society. The interrelationship of the many systems that make up aviation evolved throughout the 20th century. This incremental evolution has produced an economical, effective mode of transportation for passengers and cargo with a safety record unmatched among all other modes of transportation. Initially, human investment and ingenuity were the only bounds to growth in aviation. More recently, system expansion has encountered real and difficult physical constraints. The capacity of the Air Traffic Management system is nearing its limits. Meanwhile, efforts to increase its capacity are encountering serious technical and environmental concerns.

Aircraft systems, the Air Traffic Control systems, and airport systems represent the physical infrastructure. Human operators, who transport passengers and cargo, link these elements.

As the demand for air traffic grows, greater capacity can be achieved simply by increasing the number of aircraft. However, because airports are already

congested, more aircraft will make matters worse. As an alternative, the number airports and capacity can be expanded. However, community environmental issues severely constrain this option. Furthermore, airspace issues constrain the number of aircraft that can be operated simultaneously and safely in a given airspace. Without relieving these constraints, adding aircraft and airports will not significantly improve overall system capacity. Safety is an overriding constraint, and any change proposed must account for any potential safety consequences.

It is clear that successfully projecting the impacts of new aviation concepts and technologies will require careful analyses of the integrated system. Furthermore, consideration must be given to the intermodal relationships with the larger transportation systems (land and sea). These analyses require the construction of complex, intricate, and comprehensive system models. The models are further complicated because humans play such an important role in many aspects of aviation, from flight crew to operators of the Nation's air traffic system.

Some models, limited to treating only portions of the system, have been developed and used successfully to gain insight into a few proposed technology and process improvements. Many of these improvements are being incorporated in the FAA's Operational Evolution Program.

The Operational Evolution Program is a near-term enhancement intended to increase capacity incrementally. Revolutionary changes in the airspace system and in air vehicle designs will be needed to achieve a future air transportation system capable of meeting the long-term demand. This new air transportation system must also provide improvements in safety, accessibility, and affordability while greatly reducing the impacts on environment (e.g., noise, emissions, airport run-off). Many options are possible, and many improvements will be proposed. Only through system modeling will we be able to project realistic contributions and set priorities.

2.4 THE AIRSPACE SYSTEM

Aviation is the dominant mode for long-distance transportation in the United States. Between 1964 and 1999, scheduled revenue passenger miles increased by 1,000 percent. U.S. reliance on aviation, both domestically and internationally, will continue to grow into the 21st century. The Nation's air transportation system will need to satisfy this demand if we wish to continue to provide the American people with a transportation system that is the best in the world. Already, limits in the capacity of our air transportation are constraining growth and adversely affecting our economy. Increased demand is creating additional safety, security, energy, and environmental concerns as well.

The overall capacity of the National Aerospace System is a function of various important factors, including the design and operation of the airspace itself and the equipment that facilitates that operation. At present, the FAA and NASA are engaged in substantial efforts to modernize equipment, software, and procedures to enable significant changes in how the available airspace and airports can be used more efficiently and safely. The FAA has embarked on a new program, the Operational Evolution Plan

which will incorporate new operating concepts (e.g., "free flight") and new decision-support tools for the controllers to adapt to congested airspace and airport situations. These tools will also augment the controller's ability to handle a greater number of aircraft safely. These actions will provide some temporary relief for capacity issues in the near term, but more comprehensive changes are needed to deal with the expectations of the future.

The Government and the aerospace industry need a vision for the air transportation system of the 21st century, with challenging goals for a new system architecture to spur innovation and technology breakthroughs. The Nation needs a capability that will enable the Government, airlines, airports, and others to understand the interdependent factors that affect the dynamics of the system and their impact (e.g., alternative architectures and technologies) on the system before making major capital investments. The air transportation system must be able to provide more automated management of the Nation's airspace and airports to expand capacity and improve safety. The system must be able to manage all types of aerospace vehicles, day and night, in all weather conditions, at all airports. It

must maximize safety and efficiency and remain resilient in the event of a subsystem failure, operator error, or malicious intervention.

The Government needs to make investments in long-term research, develop the tools necessary to understand how the system operates and how changes affect its performance, and create an environment that will accelerate the transition of new technologies and concepts into operation. There are many factors constraining the Nation's transportation system today. They include weather, aircraft separation, automation, pollution, noise, and protection against terrorism. The technologies, concepts, and enabling research to address these constraints and to develop the next-generation air transportation system need to be clearly identified.

If we act now, the American people and the U.S. economy will not need to confront major future disruptions or cost increases in air transportation services.

2.4.1 THE AIRSPACE SYSTEM—WEATHER

Weather can be a friend to air travel. Favorable winds and smooth air make trips quick and comfortable. But weather is also one of aviation's most significant safety and operational challenges.

Today's Challenges

Visibility is one the most obvious and significant impacts of weather on aviation. Low visibility caused by fog and other weather conditions can pose hazards to aircraft operations and limit operations at airports. In fact, arrival rates at large airports, often drops by 30 to 50 percent when visibility is below approved minimums.

Airport takeoff and landing patterns are often established based on wind direction and other aspects of the weather. Adjusting those patterns to account for changing winds is disruptive and can take from 30 to 45 minutes. Storms are more disruptive and can cause a temporary shutdown of airport flight operation.

Trailing wake vortices are man-made atmospheric disturbances that can be operational and safety concerns. Because wake vortices cannot be seen, separation distances between aircraft are based on generalized and conservative calculations.

Those distances largely determine runway arrival and departure rates.

Impediments to visibility need to be overcome. The flight crew must have access to information on position, orientation, local traffic, and local terrain to continue safe operation of the aircraft under restricted visibility conditions.

Knowledge and prediction of weather conditions and wind patterns are essential to the effective operation of airports and airspace. Predictions need to be based on current weather conditions, not on measurements made 6 to 12 hours ago. The physical granularity of the predictions needs to be local instead of regional. Shifts in wind speed and direction need to be anticipated with accuracy. Precise location of storms and accurate forecast of their evolution and dissipation are needed in order to enable efficient and safe route planing and airport approach.

Technology Solutions

Visibility enhancements can be provided via artificial displays in the cockpit of the aircraft's surrounding environment. Such displays need to be fed by high-fidelity digital representations of the aircraft's

location and orientation, local terrain, local air traffic, and local atmospheric conditions.

To improve weather forecasting, we need to improve the process of gathering inputs for our weather models. In situ measurements are currently made at too few locations and with insufficient frequency to provide the detailed understanding of weather patterns required. Remote sensing may provide the solution. Measurements made from low-Earth orbit will need the deployment of satellite constellations with highly accurate and reliable sensors, supported by rapid data processing and dissemination.

Analytical models to predict aircraft wake vortices, combined with ground sensors to confirm the predictions, could allow separation rules to be modified when wakes are rapidly dissipated or harmlessly moved away from the runway by weather conditions. Development and application of these technologies can yield a 30 percent gain in runway arrival and departure capacity.

2.4.2 THE AIRSPACE SYSTEM—TRAFFIC OPTIMIZATION

The current approach to managing the increasing traffic volume is to reduce the size of a controller's sector so that the number of aircraft in a sector stays constant and the workload remains manageable.

Today's Challenges

Unfortunately, this approach will not work in high-density airspace. Any workload relief provided by further reduction in sector size will be offset by increased requirements for sector to sector coordination. These difficulties, together with uncertainties in weather and more will propagate into

- en route congestion with a domino effect of delays,
- limited user flexibility, and
- inefficient use of available airspace.

The FAA's Free Flight Program is taking steps to improve the efficiency and prediction of traffic flow. These steps include the use of expert systems to assist in collaborative decision-making. One needed application is to improve the coordination between national traffic flow management and local flow control. Advances in decision-support tool technologies, together with improved data links, will

allow movement toward more distributed air and ground traffic management.

These improvements are incremental and will be useful in dealing with capacity issues in the near term. Long-term solutions require more substantial changes.

Technology Solutions

One potential major change in the system operation is to move away from sector-based control and toward "super-sectors." Automation of the ATM can assist the controller and pilot in assuring aircraft separation while meeting all flow constraints. Such automation will include some degree of airborne self-separation, ground-based separation controlled by intelligent agents, integrated negotiated air and ground separation, and controller-based separation. The level of aircraft equipage, weather, traffic density, contingencies, and other factors will determine how the share of separation responsibility will be applied among these parties.

Providing a systemwide optimization capability will require moving away from the stratification of planning time

horizons between the System Command Center, local flow control, and sector control that characterize today's system. Advanced planning and optimization techniques, such as genetic algorithms and multifunctional optimization, will be applied to enable continuous decisionmaking over all time horizons, treating weather, demand and capacity requirements, and other factors influencing traffic probabilistically.

The interaction between the human operator and a highly automated air transportation system is critical. The system cannot be designed under the assumption that the human will step in and revert to today's operation in the event of a failure. People will retain the ultimate responsibility for the system operation. The anticipated level of automation will require the development of an interactive computer-based monitoring and goal-setting system. This system will assist the human in managing air traffic in response to varying conditions and subsystem failures. This is a new area of development within computer science, and human factors that is needed to the move forward.

2.4.3 THE AIRSPACE SYSTEM—HIGH-FLOW AIRPORTS

The flow of airport traffic is an important component of the overall air traffic system. The efficient flow of passengers and aircraft at airports can provide significant advantage; inefficient traffic flows can turn airports into bottlenecks and result in congestion and delays.

Today's Challenges

Before an aircraft is prepared to take off, it must take on a load of passengers or cargo at a terminal, then travel to the starting point of a runway. Similarly, when an aircraft lands, it must travel from the runway to the terminal to offload passengers or cargo. The maneuvering of aircraft - vehicles as large as buildings - on the ground through dispersed ground support vehicles and equipment must be well orchestrated to maintain efficiency and preserve safety. Winds dictate the direction of airport traffic. It is preferable for aircraft to take off and land into a headwind. When winds shift direction, redirection of aircraft preparing for takeoff and revectoring of approaching aircraft preparing to land may be required. This can be a lengthy and inefficient process involving not only the aircraft, but the ground vehicles as well.

Two factors, visibility and safe separation between airplanes, have a major impact on airport traffic. During good visibility conditions, pilots can use their vision to compensate for uncertainties in their instrumentation. In poor weather or other conditions causing low visibility, rules and regulations must guarantee aircraft separation. For example, when separation between runways is below safe limits and one runway must be shut down, the airport's capacity decreases dramatically.

Meanwhile, the economic benefits of airport hub-and-spoke architecture have placed immense traffic demands on about 60 airports in the United States and resulted in underutilization of thousands of other existing airfields.

Technology Solutions

Early introduction of integrated arrival, departure, and surface decision-support tools is reflected in the FAA's current plan. These decision-support tools hold the promise of increasing capacity gains within the present system.

Several technologies are being pursued to provide situational awareness through synthetic vision. These will have the effect of providing daytime-equivalent

visibility in all weather and lighting conditions.

Following are some airport design and operational models under research:

- *Closely Spaced Aircraft Takeoff and Landing*—precision navigation and intelligent controls to support simultaneous group landing and takeoff of multiple aircraft.
- *Dynamically reconfigurable runway and taxiway location operations*—a solid paved area would define airports, runways and taxiways that could be reconfigured to make use of advanced scheduling and planning logic to maximize the throughput.
- *Dynamic Virtual Ramp and Control Towers*—using virtual reality to perform tower functions.
- *Smart Non-Towered Airports*—using all the developments above with advanced information systems to offer the potential of high-density operations in all weather conditions to virtually any small airport. This will provide quantum change in accessibility to all communities, large and small.

2.4.4 THE AIRSPACE SYSTEM—COMMUNICATIONS, NAVIGATION, AND SURVEILLANCE

Currently, aviation communications, navigation, and surveillance (CNS) are accomplished primarily through analog voice communications, ground-based navigational aids, onboard inertial aids, and ground-based radar. This is based on decades old technology. While today this is stable, safe, and redundant, it is at its limit and is a barrier to growth.

Today's Challenges

The current voice-based system is near capacity. Basically, too many pilot-controlled messages over too few radio channels in at the same time. This older technology cannot be extended to support the data-intensive automated decision-support systems of the future.

Navigation and airspace surveillance using ground-based systems cover only a small fraction of the U.S. and global airspace. Major coverage lapses exist in the airspace over remote areas and the world's oceans.

The future Air Traffic Management systems will be information-intensive. That system will move away from central control to more distributed decision-making. Similarly, plans to improve air traffic safety are also demanding

increased situation awareness in the cockpit, which must be provided through increased air-to-ground and air-to-air communications in real time. This distributed architecture will rely on characteristics such as precise navigation information and comprehensive global coverage currently not available.

Technology Solutions

High-bandwidth, highly reliable, secure networks with global connectivity supporting information-intensive applications will be required. These networks will provide ubiquitous access to describe the dynamically changing aviation environment and the national airspace status. Information such as traffic flow, navigational aids, airspace constraints, and weather will be transmitted to support cockpit and ground-based displays, decision-support tools, and automated system operation.

Satellite-based systems will be a major part of these networks; provide communications links, positioning signals, and sensor-derived information. Communications will be digital, using spectrum-efficient communication technologies that must be robust under all

weather and hazard conditions. Active and passive systems will combine to provide high-precision and high-integrity navigation and surveillance. They will interact with ground-based and cockpit automated command and display systems. These active and passive systems will be standards-based to allow broad participation by a variety of aviation equipage providers.

2.5 REVOLUTIONARY VEHICLES

Revolutionary new air vehicles will enable a new future of aviation and mobility. Technical challenges confronting the designs of these vehicles must address not only the issues of flight, but also urgent social and environmental issues.

Today's Challenges

Noise emitted by aircraft propulsion systems and aerodynamic surfaces continues to be a concern for airport communities. Even military aircraft are no longer immune to such concerns. The visionary goal is to make airports good neighbors. People should have the option to choose to locate near airports and take advantage of the opportunities and the convenience without the need to be concerned about excessive noise. Technology can be applied to limit the extent of objectionable noise levels generated by air vehicles to the airport boundaries.

Aircraft emissions are not yet a concern at the global level, but they are a local concern for some airport communities. Air traffic growth will increase the number of communities reacting to

aircraft emissions and will increase emissions' global significance.

Because aircraft have a long operating lifespan, it takes many years for new technologies to have a significant influence on the average characteristics of the commercial fleet. This lag time dictates that technology solutions must be sought today to protect our environment in the future.

Air travel is the safest mode of transportation available today; however, air accidents get more national and global public attention than all other modes of transportation. To maintain the public's confidence in aviation, the number of accidents must be reduced. If the accident rate does not change and air traffic doubles over the next two decades, the number of incidents will double. Technology can make a big difference.

Revolutionary modes of air transportation are in demand in a growing number of diverse areas. The military has a need for surveillance. Once filled by such aircraft as the U-2 and the SR-71, aircraft needs have changed to low-speed, low-altitude, and low-detection. The airlines are pushing at both ends of the size spectrum.

More load-carrying capability is needed, as are smaller commuter airplanes that can access urban centers economically. Meanwhile, the private pilot and airplane owner sector is interested in airplanes that provide speed and range, as well as convenience and economic versatility equal to that of automobiles.

Technology Solutions

Technologies are emerging that will facilitate these varied needs. Already information technologies are enabling major changes in aviation. In the future, we can expect more automated operations of both the airspace and the aircraft.

Aviation materials have improved dramatically over the last century, from wood to aluminum and on to composites. The coming revolution in nanotechnologies will take that progress further.

Likewise, biological sciences are providing a new way to look at aircraft. Mimicking nature by providing muscle-like actuators to change aerodynamic form, nervous-system-like sensing, self-healing systems, and adaptive fault-tolerant controls to enhance flight safety leading to more reliable air vehicles.

2.5.1 REVOLUTIONARY VEHICLES—CAPABILITIES

Evolving technologies hold the promise of creating a whole new era in aviation to meet the transportation challenges of the 21st century. Advanced capabilities will lead to more personal air travel, spark new business opportunities, enhance our national defense and reduce environmental impacts that are today deterrents to growth

Future Possibilities

Large, Long-Haul, and Long-Duration Transportation

Military and commercial customers need large, long-range aircraft for global force projection and the transportation of people and goods. Airframe configurations under consideration range from blended wing bodies, joined wings, or multi-fuselage designs integrating a variety of advances across many aeronautics disciplines to produce highly efficient aircraft.

Increased Speed

In today's competitive, time-critical world market, speed is important. High-speed capability will allow the business traveler to redefine the 12-hour workday. At

supersonic speeds, worldwide coverage in 10 hours and a time savings of up to 50 percent for transcontinental crossings are possible. Supersonic air vehicles will open up markets beyond traditional scheduled service such as high-speed parcel delivery to support just-in-time manufacturing, as well as military transport and special operations.

Supersonic cruise flight remains a challenging aerospace frontier. The barriers to sustained supersonic flight for military and commercial applications are sonic boom for overland flights and takeoff and landing noise. New vehicle concepts are required, with significant advances in lift/drag ratio, specific fuel consumption, lightweight structures, local shape optimization, and flow control.

Runway Independence

Doorstep-to-destination mobility will drive vehicle requirements and provide multi-level highways in the sky. New vertical lift and extremely short takeoff and landing capabilities using directed thrust from very light engines will provide a degree of runway independence much like today's advanced rotorcraft and tilt rotor vehicles. Cargo-sized aircraft that

can take off and land in as little as a 700-ft distance will allow the expansion of commerce to areas not normally served by other transportation means.

Autonomous Operations

Uninhabited aircraft are envisioned that fly at altitudes above 80,000 feet and stay aloft for weeks or months. Both military and commercial missions are envisioned, including reconnaissance, environmental monitoring, communications, and weapons platforms. Small autonomous aircraft will provide important new mission capabilities for surveillance and monitoring of dangerous or high-risk areas. Equipped with new sensors and control systems, the vehicles will look for and identify toxic and biological contaminants and other military threats.

2.5.2 REVOLUTIONARY VEHICLES—TECHNOLOGIES

The air vehicles of today bear little resemblance to those of the time of the Wright brothers. Gone are the double wings supported by an assortment of wires and struts. Wood frames with cloth coverings have been replaced by monocoque aluminum construction. The belt-driven propellers have given way to jets and turboprops. Landing gears retract, and electronics and optical fiber replace mechanical linkages and. Similarly, tomorrow's air vehicles will bear little resemblance to those of today.

Today's Challenges

Today's aircraft weigh twice as much, use 75 percent more fuel, and create four times the noise than the technically possible, "to be" aircraft. Today control systems rely on the movement of nonredundant aerodynamic surfaces with triplex redundant command signals to alter the airflow around the vehicle and achieve the desired result. This adds weight, takes space, and is a hazard in case the movement is impeded.

Technology Solutions

New Materials

High strength nanomaterials may help aircraft withstand crashes and protect

passengers. Future aircraft also may benefit from emerging molecular research and nanotechnology. Revolutionary composites promise to be 100 times stronger than steel and a sixth of the weight. Future aircraft could weigh half of aircraft today, be extremely flexible, reform wing shape for optimal flight, resist damage, increase thrust-to-weight ratio up to 50 percent, and self-heal.

Active Flow Control

Vehicle control systems may be implemented without moving control surfaces. A combination of propulsive forces, micro surface actuators, and fluidic devices operated by an intelligent flight control system will provide a level of redundancy and safety not available today.

Propulsion and Power

Other technology might replace life-limiting, complex rotating machinery with hybrid engines using pulse-detonation concepts and embedded intelligent engine control capability. Advances in electrical energy generation and storage may provide fan-driven thrust using highly efficient, compact electric motors powered by advanced hydrogen-oxygen fuel cells. Several issues must be resolved

to use hydrogen as a fuel, including a nationwide infrastructure for delivering fuel to vehicles. Success could end dependence on foreign energy sources for transportation.

Intelligent Aircraft

Intelligent systems of smart sensors, microprocessors, and adaptive controls will monitor performance and environment and help operators avoid danger. Such intelligent systems will function like a nerve network and stimulate aircraft to respond and even change shape. These systems also will sense damage or impending failure.

Design Tools

Computational tools that apply advanced information will be required to take full advantage of nanotechnology materials. Development costs will drop and production schedules will compress as high-fidelity, collaborative environments with human interfaces will simulate the product life cycle. Computational tools will integrate complex systems and offset diminishing U.S. design experience.

2.5.3 REVOLUTIONARY VEHICLES—NOISE

Today's Challenges

Noise is typically the primary community objection to airport or runway expansions. Airports once built in remote areas are now located in the midst of sprawling communities. They are subject to an increasing number of noise restrictions affecting their operations and those of aircraft. Since 1980, the number of noise restrictions at airports worldwide has grown from 250 to over 800.

The U.S. has spent more than \$4 billion from the Aviation Trust Fund and Passenger Facility Charges over the last 20 years to mitigate airport noise (e.g., sound-insulating nearby homes, building protective barriers). Reducing the noise impact on communities will be a key issue for 21st century aviation.

Analysis of aircraft noise at Chicago O'Hare International Airport provides a useful example of the importance of reducing aircraft-generated noise. Using the baseline 1997 aviation fleet noise-level contours, noise levels extend many miles from the airport and affect approximately 600,000 people in the surrounding community. A quieter fleet of aircraft with a 10-dB reduction in noise at the source will reduce that impact to

approximately 55,000 people. To eliminate noise as a major issue, a noise reduction of 20 dB is needed. At this level, objectionable noise levels will not extend beyond the airport boundary.

Technology Solutions

One of the keys to achieving noise reduction is to improve our understanding of the sources of aircraft noise generation. There are two major sources of noise: the engines and the airframe. Our present prediction capability is largely empirical. New computational and experimental tools are being developed that will allow more comprehensive modeling and understanding of noise sources and propagation characteristics.

Full computational simulation of airflow in engines and in the exhaust stream will provide designers with an opportunity to address noise early in the design phase of new engines and vehicles. This improved understanding and simulation capability will result in new vehicle concepts that are designed from the beginning with noise as a principal constraint.

Our current knowledge of noise generation allows us to predict that future revolutionary vehicles will use propulsion

systems with low-speed fans and nozzles with low jet exit velocities to reduce generated noise levels.

Quieting the propulsion system alone will not be enough—advanced vehicle concepts with integrated propulsion systems, advanced materials, and innovative noise shielding techniques will be required. A blended wing body concept is one such concept. Rather than having a few distinct sources of propulsion (engines), such a vehicle distributes the propulsion system across its upper surface and uses the vehicle to prevent the noise from propagating to the ground.

Vehicles of the future will incorporate morphing structures that provide adaptive seamless control surfaces, as well as active flow and noise control to mitigate the turbulent wakes and noise sources on the vehicle.

2.5.4 REVOLUTIONARY VEHICLES—EMISSIONS

Today's Challenges

While not yet a significant concern at the global level, aircraft emissions are a concern in some communities. Already some European airports are imposing landing fees based on aircraft emissions. In the United States, some of the busiest commercial airports are unable to increase flight operations because they are located in Environmental Protection Agency-designated “non-attainment areas,” where air pollution levels persistently exceed the national standard. Failure to meet the standard gives the Federal Government the right to suspend Federal transportation funds. To avoid more stringent emission restrictions, some U.S. airports are starting to require that all rental and airport vehicles be powered by natural gas. To enable further expansion of airport operations, nitrogen oxides (NO_x) emissions from future aircraft engines must be reduced in order to limit resulting ground-level ozone.

As demand for air travel expands over the 21st century and air traffic doubles over the next 20 years, emissions will become an even greater issue. Even with today's best technology improvements, recent

assessments project a 400 percent increase in global NO_x emissions and a 300 percent increase in greenhouse carbon dioxide (CO₂) by 2050.

Technology Solutions

Revolutionary propulsion concepts that use alternate fuels and intelligent engines and combustors will dramatically reduce NO_x and CO₂ emissions. Intelligent combustors using sensors and actuators will be used to continually monitor the combustion process and minimize the amount of fuel burned thus reducing the CO₂. Combining smart combustors with new materials can precisely control the fuel to air combination dramatically reduce NO_x emissions.

Greenhouse gas CO₂ emissions are directly related to fuel consumption. Reducing CO₂ emissions requires more fuel-efficient aircraft and propulsion systems. New, innovative vehicle concepts such as strut-braced wings, blended wing bodies, and innovative propulsion cycles like vaneless, counter-rotating turbomachinery show great potential. Distributed propulsion systems integrated into vehicle airframes, ultra-lightweight structures, smart structures,

and controls that shape the vehicle dynamically to optimize for minimum drag over each mission segment offer additional benefits. Advanced vehicle technologies for improving aerodynamic performance and specific fuel consumption can reduce fuel consumption by 10 to 20 percent. Advanced propulsion systems with improved propulsive efficiency can achieve a further reduction of 20 to 30 percent.

It may be possible to eliminate objectionable emissions altogether. Use of advanced fuel cells and electric propulsion systems will drive both CO₂ and NO_x emissions to near zero while dramatically reducing noise. For example, replacing hydrocarbon-based fuels with hydrogen. This, however, creates a new set of technology challenges regarding safe and ubiquitous generation, storage, and distribution of this fuel on a national and global scale.

2.5.5 REVOLUTIONARY VEHICLES—SAFETY

Today's Challenges

As aviation continues to grow, there is a concern that unless steps are taken to drastically reduce accident rates, increased flights will lead to more accidents. The National Civil Aviation Review Commission endorsed a goal to cut the fatal accident rate by 80 percent by 2007.

Controlled-flight-into-terrain accidents represent the single greatest risk to aircraft, crews, and passengers. This occurs when an airworthy aircraft, under the control of the flight crew, is flown unintentionally into terrain, obstacles, or water, with no prior awareness by the crew. This type of accident can occur during most phases of flight, but is more common during the approach and landing.

Limited visibility is the single greatest risk element in peacetime military, commercial, and general aviation. When visibility is reduced—at night or in poor weather—piloting errors, errors that would otherwise be quickly corrected in clear daylight conditions, can have fatal consequences.

Pilots, ground handlers, mechanics, airline dispatchers, and air traffic controllers all have vital safety roles. Human decisions also extend to the engineering design, build, and certification of the aircraft. As aviation gets more complex, humans and the mistakes they are prone to make will be the focus of much-needed improvements.

Hardware and software failures account for roughly 25 percent of aviation's fatal accidents. The increased complexity of air vehicles will make it more difficult to identify and rectify all potential failure modes in the design phase. Aircraft of the future will have the ability to heal and reconfigure in flight.

Technology Solutions

Precision aircraft position, local traffic knowledge, accurate digital terrain and obstacle maps, and advanced cockpit displays will produce a clear picture of the outside world in the cockpit, no matter what the actual visibility or time of day. Such capabilities will allow pilots to avoid danger in the air as well as on the ground.

Human-centered design methods for flight decks and aviation systems designed to balance human and automation functions will minimize the opportunity for human error and maximize robustness of aviation systems. Human behavior and decision-making models will better predict information needs and error susceptibility, which will lead to error-tolerant designs.

Distributed adaptive control systems with real-time system reconfiguration will provide multiple layers of redundancy seamlessly by using remaining functionality to control damaged air vehicles. Health-monitoring systems will provide heightened ability to detect and identify non-normal system operations in real time. Onboard sensing, trending, and performance analyses will allow hardware, software, or procedural intervention to correct developing problems.

Integrated onboard precision navigation, digital terrain models, and dynamic collision-avoidance systems will restrict the maneuvers of aircraft. This will result in air vehicles that refuse to crash - avoiding known terrain features, other flying vehicles, and incursions into restricted air space.

2.6 AVIATION SECURITY AND SAFETY

Today's Challenges

Aviation has a long-standing tradition of being the safest among all modes of transportation. The rate of accidents and fatalities on a per-passenger-mile basis for commercial aviation is at least a factor of two lower than that achieved by any other mode of transportation. Nevertheless aviation disasters must be prevented and the public's trust in aviation security and safety reestablished.

As with other modes of transportation, aviation hazards can be sorted into two major categories. The first set of hazards relates to the undesirable consequences of unintentional actions or failures. These are addressed by the topic of aviation safety. Hazards relating to the consequences of intentional actions or failures are addressed by aviation security. In both cases, the most desirable approach is early identification and neutralization. Failing that, various approaches to mitigation must be employed.

There are extensive discussions ongoing at the national level on the subjects of airport security, as well as passenger and baggage screening, which are outside the scope of this

blueprint. Rather, this blueprint addresses challenges and technology solutions relating to the design, construction and operation of aircraft systems and the airspace management system.

The terrorist attacks of September 11, 2001, shocked the Nation by showing how terrorists used commercial aircraft as weapons of massive destruction. Our first priority is to prevent terrorists from boarding commercial aircraft or getting any type of weapon onboard. The second priority is to prevent terrorists from overpowering the crew and taking control of the aircraft if they do get onboard. Only if the other interventions are unsuccessful will we need to deal with preventing hijackers from crashing the aircraft. In that case, concepts that might preserve the lives of the passengers and crew are preferred over any action that results in the destruction of the aircraft.

Other hazards addressed under the topic of security include aircraft sabotage; disruption of the command, navigation, and surveillance infrastructure; and electronic viruses.

Aviation safety hazards include human errors those made by pilots, airspace system managers, or aircraft designers; equipment failure; loss of control; and bad weather conditions.

Technology Solutions

Technology can help, but often the most challenging aspects are not technical, but policy, acceptance, safety, and implementation issues that would have to be resolved before a decision to use the concept could be made. If any of these concepts were to be considered for implementation, it should be demonstrated on commercial transport in an operational situation. Before pursuing such demonstrations, the policy, acceptance, safety and implementation issues must be addressed.

The blueprint addresses a range of technologies that can be applied to specific problem areas. These technologies are aircraft and systems hardening, enhanced flight procedures, surveillance and intervention, and information technology for prevention.

2.6.1 AVIATION SECURITY AND SAFETY—AIRCRAFT HARDENING

Equipment failure and loss of control, possible contributors to the November 12, 2001, crash of American Airline flight 587 in New York City, account for roughly 25 percent of aviation's fatal accidents. There is a growing concern that as the complexity of air vehicles increases, the designers will be increasingly challenged to understand failure paths and their potential consequences. Aircraft need to be more resilient and tolerate to unforeseen situations.

Today's Challenges

As the demand for onboard information-intensive applications grows, today's analog communication systems will give way to high-bandwidth digital systems. These new capabilities will, however, result in new areas for intrusion and therefore added security protection.

Deaths in aircraft accidents often result from fire and smoke inhalation. Because aircraft travel long distances, they are laden with highly flammable fuel; in the event of a crash, the fuel is as much of a hazard as the violence of the crash itself. Protecting the passengers and crew from the dangers

of fuel-fed fire and smoke is one of the major aviation safety challenges.

Technology Solutions

The tragedy of Pan American World Airways Flight 103 on December 21, 1988, still haunts the world of aviation. The threat of a bomb on a jumbo jet is too real to be ignored. Measures beyond airport security are needed to protect the lives of those onboard. One possible solution is blast resistant luggage containers a focus of FAA research. However, with the development of lightweight extremely strong material that will absorb the energy from a blast those containers and possibly the aircraft fuselage can be spared from significant damage. This development will not replace airport security efforts; rather, it will provides us with added protection.

Incipient hardware failures have characteristic signatures. Detecting these signatures, interpreting their significance, and alerting the flight and maintenance crew will soon be commonplace in aviation. Self-healing systems may be enabled to rectify the problem before a catastrophic situation arises. Flight controls may be

reconfigured in flight to avoid stressing the system and will delay the failure; also, adaptive controls could compensate for failed components and help land the aircraft safely.

Human-centered design methods for flight decks and aviation systems designed to balance human and automation functions will minimize opportunity for human error and maximize robustness of aviation systems. Human behavior and decision-making models will better predict the information needed at crucial times, leading to error-tolerant designs.

Secure networks will provide a first line of defense against electronic intruders. Onboard electronic virus detection and inoculation will protect complex software-driven applications. Reconfigurable computers will adapt in real time to failures and malfunctions, allowing the safe return of the passengers and flight crews.

Self-extinguishing fuels will mitigate the consequences of accidents and malicious use of fuel-laden aircraft.

2.6.2 AVIATION SECURITY AND SAFETY—FLIGHT PROCEDURES AND MONITORING

Today's Challenges

Airspace management is becoming more complex. The airspace is increasingly more intricate. The number and types of protected areas are increasing, and there is more air traffic. Precise guidance of traffic in this environment is difficult and requires a number of concomitant improvements in support functions. Likewise, flying in this complex airspace is becoming more demanding. In addition to the physical constraints imposed by terrain and protected areas, more restrictions are being placed on approach and takeoff corridors to control noise. This is an added complexity that needs to be safely addressed in all weather and atmospheric (wake vortex) conditions.

Although the term “as the crow flies” implies going from point to point in straight lines, commercial airliners do not move that way. Moving at speeds in the neighborhood of 600 miles per hour, turns are gradual arcs that sweep broadly across the sky. When asked to change heading by ground controllers, airliners respond with a significant time lag that must be anticipated by the party making the request.

Detection of an aircraft and predicting its flight path are not always possible. Some rural areas do not have adequate radar coverage, and aircraft transponders are not always active. This can be due to a hardware malfunction or they can be intentionally deactivated as in the case of the September 11, 2001, terrorist attacks.

Technology Solutions

The first requirement for improving management of the complex airspace is to provide continuous precise navigation and position information. This improved navigation information must be available onboard and on the ground. Increased coverage of remote areas and airspace over the oceans will be provided by satellite-based redundant navigation systems. Ground systems used to track aircraft will propagate trajectories using curved path approaches, avoiding terrain and protected areas, and accounting for local traffic and access restrictions. This modeling effort will predict air traffic, optimize traffic flow, and identify areas of potential congestion to take steps to minimize risk to aircraft.

Combining continuous position information and the modeling effort will provide precision flight paths and real-time monitoring of air traffic. Aircraft deviating from the predicted flight path will be easily identified. Alerts will draw attention to the violating aircraft in order for the deviation to be resolved.

2.6.3 AVIATION SECURITY AND SAFETY—SURVEILLANCE AND INTERVENTION

Today's Challenges

Intrusion into controlled airspace is becoming an increasing concern. The severe restrictions placed on the operations of Reagan National Airport and the grounding of general aviation aircraft at airports near the Nation's Capital reflect this concern and the aviation community's inability to address it by other means.

Once the air traffic controllers became aware of the developing situations during the terrorist attacks of September 11, 2001, all they could do was notify authorities on the ground and watch. Today, the situation is not much better. Military aircraft on 24-hour patrol can now be vectored to aircraft that are deviating from their assigned flight path. Military commanders are authorized to order the downing of civilian aircraft that are thought to pose a threat to people on the ground. A better set of options is urgently needed.

All commercial aircraft carry voice cockpit recorders and flight data recorders. These instruments have proven to be invaluable in aircraft

accident investigations. However, because the information is stored on physical media, these instruments provide after-the-fact information and are of no use in resolving problems in real time.

Technology Solutions

Synthetic vision will display local terrain conditions in the cockpit regardless of visibility. Local air traffic, navigation information and weather conditions will be presented, giving the crew an increased awareness of the aircraft's surroundings. Controlled airspace will be displayed in three dimensions.

Having all this information available onboard and in real time will enable a whole new way of flying. Onboard computers will be able to project aircraft trajectories and plan maneuvers to avoid protected areas or areas that are otherwise dangerous. This technology will become the "conscience" of the aircraft, refusing to let it perform unauthorized airspace intrusions and refusing to let a controllable aircraft crash. Combined with a secure command link and proper

flight controls, this technology will give controllers on the ground the ability to direct an errant aircraft to a safe and secure landing site.

Two-way wideband data links between aircraft and the ground could revolutionize the information exchange of today and enable a whole new era in aviation safety and security. The forward link from the ground to the aircraft will provide a new era of situation awareness in the cockpit. The return link from the aircraft to the ground will not only transport voice communications, but may also include selected security video from inside the aircraft.

Additional information transmitted to the ground in real time will include much of what is recorded today by the flight data recorders, only this data will be available to help assess the aircraft's status and resolve emerging issues before they become catastrophic. Potential uses include responding to in-flight anomaly resolution or detect a security breach on an aircraft and providing the information needed to overcome malicious intents.

2.6.4 AVIATION SECURITY AND SAFETY—INFORMATION TECHNOLOGY

Today's Challenges

Over 700 million passengers board airplanes in the United States each year. Pre-departure passenger screening must ensure that none of these passengers presents a threat to the safety of the flight.

Today's system makes use of passenger reservation information to make this assessment, but this information is clearly inadequate. The passenger screening system of the future must be more intelligent and comprehensive, without adding excessive time or cost to the process.

In addition to improving pre-departure security measures, an effective diagnostic system is needed to measure the performance of the security system and to identify emerging trends of concern to the appropriate authorities. Such a system will need to be able to accept and analyze large amounts of data, and provide meaningful interpretations of the results very quickly.

Flights in progress are continuously monitored by radar within the air traffic facilities. However, with current

display systems, it is not quickly apparent when an airplane makes a significant deviation from its intended flight path. The air traffic controllers need to have better information about potentially threatening aircraft, without burdening their ongoing responsibilities for managing the air traffic safely.

Technology Solutions

An automated passenger identification and threat assessment system can be developed and will provide positive identification of passengers. It will also perform a real-time evaluation of security concerns that may require additional scrutiny. Using nonintrusive biometric devices, passengers will be uniquely identified at the time of check-in and again prior to boarding the aircraft.

Accessing a wide variety of databases using intelligent search engines, a much better assessment of security will be possible. Together these systems will ensure that passengers who board aircraft do not pose a threat to the safe completion of the flight.

The Aviation Safety Reporting System, currently managed by NASA, has a

long history of receiving and analyzing safety issues. This system can be extended to include security concerns as well, creating an early warning system that will correct shortcomings in the aviation security system before a vulnerability is exploited. Since the system is secure, voluntary, and confidential, it is widely trusted and used.

Air traffic controllers are in an ideal situation to monitor airplanes in flight. New expert advisory systems will assist controllers in identifying flights that are deviating from their intended path. The system will provide additional assistance in taking appropriate action notifying the proper authorities, ensuring the safety of neighboring aircraft, and advising the possible intentions of the intruder. This will enable an automated, and thus much more rapid, response to threats than is possible today.

3.0 A STATE OF THE ART EDUCATED WORKFORCE

3.1 STATE OF THE ART EDUCATED WORKFORCE—APPROACH TO EDUCATION

Approach to Education

Over the next two decades, the field of aeronautics will undergo dramatic revolutionary change, placing unanticipated demands on its very foundation- a highly skilled and technically proficient workforce. The United States must restructure its aeronautical education paradigm or risk failing to produce the talent necessary to create this new era in aviation. We have considered the Approach to Educating relative to the future workforce and the continuing education after graduation. The second perspective is the manner in which aerospace research, technology, and product development are accomplished in the future- Accomplishing the Enterprise Mission.

To meet this challenge, we must adapt our educational system, motivate

students to undertake the challenge, and provide the leadership they will need to focus their enthusiasm. This will happen only through a concerted partnership among government, industry, and academia.

The first step is to establish an exciting national vision for aviation, one that motivates young people to endure the difficult educational curriculum needed to pursue careers in aerospace. Public outreach programs at all levels can help in this regard. More importantly, a vigorous and visionary program in aeronautics is needed to entice the most highly qualified people to seek careers in aviation.

The increasing pace of technological change, the complexity of engineering systems and the need for global

awareness are impacting the way scientists and engineers are educated. The curriculum must be structured to encourage the application of non-traditional disciplines in problem solving. Virtual and interactive learning environments will take advantage of advances in simulation, virtual reality, teleconferencing and networking to enhance the relevance and scope of the student experience.

We must demand and promote lifelong learning among our aviation professionals. Learning centers ranging from interdisciplinary research centers to distance education programs and consortia of universities or aerospace institutes can all contribute to this objective.

3.2 STATE OF THE ART EDUCATED WORKFORCE—ACCOMPLISHING THE ENTERPRISE MISSION

Accomplishing the Mission

The American aerospace workforce is aging. The average age of those employed in the aerospace industry is slightly above 47 years. For example, NASA currently loses senior R&D expertise at almost twice the rate of incoming new talent. The average age of engineers and scientists in professional aerospace engineering societies is approaching 57 years. In addition, today's workforce-in-training is choosing other career fields. These trends pose a threat to the long-term vitality of aviation in the United States.

The support of aerospace research and development has declined by almost 50% over the past 15 years. As a result, NASA is losing the externally acquired expertise necessary to supplement NASA competencies and

explore exciting new concepts. Sustained government, university and industry partnerships must be developed to avert the loss of critical skills and expertise necessary for the 21st century aviation industry.

Meanwhile, aeronautics is changing. Collaborative engineering is changing the design process. Multidisciplinary research, the application of seemingly disconnected technologies in combination, is yielding technical synergy and producing new aviation materials and systems. Nontraditional, geographically dispersed, technical and scientific disciplines (e.g., information technology and biotechnology) are becoming more relevant to aviation, and they are projected to change how air vehicles are designed and operated. These multidisciplinary efforts are changing the landscape of the aviation

industry workforce, moving it away from a workforce and workplace of the present.

The creation of virtual research laboratories where many disciplines, at a variety of locations, can interact and collaborate on projects of the future will enhance the effectiveness of the aviation knowledge base. Similar technological advances in distance learning will support the life-long-learning of aviation professionals-keeping them abreast of technological and scientific advances on a global scale. Intelligent learning systems of the possibility of distilling and refining the vast global knowledge base to access the crucial information to fill the knowledge gaps in the application of aerospace technology.

4.0 SUMMARY AND ACTIONS

4.1 SUMMARY

Advances in technology have paced aviation's evolution throughout its first century. The Wright brothers initiated the first era in aviation in 1903. Their breakthrough flight not only depended on their technical innovations, including their pioneering efforts in lateral flight controls, but it also capitalized on the growing understanding of fundamental aerodynamics and the newly developed internal combustion gasoline engine. Near the end of World War II, first Germany, then Britain developed the jet engine, leading to the second era of aviation. Further refinements in engine technology (axial compressor), combined with new aerodynamic principles (swept wings) enabled the development of the KC-135. Its commercial twin the Boeing 707 and the Douglas DC-8 set off a rapid conversion of commercial aviation to the jet age in the 1960s. The application of new technologies (high bypass ratio turbofan, supercritical airfoils, fly-by-wire) and new approaches to the problem of air traffic control (radio navigation, radar tracking with onboard transponders) allowed the societal impact of the jet age to be truly global and extend far down the economic ladder. As the jet age became an integral part of our society, the

technology improvements in aviation have become incremental rather than revolutionary.

As the Nation and the world become more dependent on the ability to move goods and people faster and more efficiently by air, important and difficult challenges have emerged. Saturation of the civilian air transportation system is causing delays and disruptions in air service.

Furthermore, legitimate concerns about environmental issues such as noise and emissions are constraining the physical expansion of much of the worldwide aviation infrastructure. Our military challenges have become more complex. The fight against international terrorism has replaced the Cold War. The terrorist attacks of September 11, 2001, shocked the Nation and the world. There is a need to reestablish the public's trust in aviation security and safety.

The NASA Aeronautics Blueprint lays out a technology vision for the next era in aviation. This technology vision must be worked as part of a broad national plan that involves research organizations such as NASA and academia, as well as the organizations responsible for applying the research products, such as DoD, DOT, the FAA, and industry.

New technologies and operational concepts, both nearly in hand and in early development, offer the potential to far surpass those constraints and create a new level of performance and capability in aviation. NASA proposes a focused technology strategy that addresses key challenges in today's aviation system. The specific challenges and the technology solutions NASA proposes to pursue are organized into four primary focus areas:

- advanced concepts for the airspace system,
- revolutionary vehicles with significantly greater performance,
- a new paradigm for aviation security and safety, and
- assured development of the capable workforce for the future.

The accelerating pace of technology advances worldwide introduces an element of urgency. If we fail to act now, the American people face a future characterized by constrained mobility and unrealized economic growth, with continued disruptions and cost increases in air transportation services.

4.2 NASA'S FIRST STEPS TO ACHIEVE THE VISION

NASA is embarking on technological and cultural changes for the 21st century. Key to such changes is the ability to determine, through objective means, our progress in achieving our goals. Because NASA addresses aeronautical technologies that are very forward-looking, and because the aviation system is very complex, determining the extent to which interesting technologies will work to the public good is not an easy task. System analyses will provide much-needed insight. Over the past decade, we have shown that system models can be extremely advantageous in understanding the dynamics of the aviation system and in making decisions on how to improve its performance and safety. Advances in information technologies have already begun to provide insight. Our modeling efforts are addressing complex systems with increased precision and speed, ultimately leading to comprehensive system models that will be invaluable in prioritizing and evaluating potential technology solutions.

Answers derived from this modeling activity will guide our efforts to realign

and strengthen our workforce to best address our upcoming challenges. We will revitalize facilities that are critical to our future goals and eliminate those that are projected to be of marginal or little use. This will create opportunities for new partnerships and new ways of doing business, efforts that we are eager to tackle.

Just as the technology of flying machines is poised to change, the tools used to analyze, design, and manufacture them must also change. As the technical disciplines applied in the design and fabrication of flying machines expands, so will the workforce that will be employed. New disciplines to aeronautics such as information technology, nanotechnology, and biotechnology are changing our concepts of flying machines. These will be addressed by a geographically dispersed workforce collaborating as virtual design teams needing to stay current with a rapidly advancing state of the art.

Future advances with aviation applications will more likely be realized from the convergence of many

technologies rather than from progress in any single area of research. Therefore we need to restructure our approach and portfolio for long-term research. To enhance our probability of success, we will

- establish new national technology competencies,
- expand our approach to University Research Center partnerships, and
- continue to strengthen interagency partnerships to meet national needs.

Only through such a broad-based approach are we likely to continue to provide the leadership necessary to ensure that aeronautics will make a positive contribution to continued economic growth, a national defense second to none, and an improved quality of life for the American people.