Spring 2004

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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The BRIDGE

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Editor's Note

C. Dan Mote Jr. is president and Glenn Martin Institute Professor of Engineering, University of Maryland, College Park, and an NAE member.

Centennial of Aviation

December 17, 2003, at 10:35 a.m. marked the centennial of the first powered, controlled, heavier-than-air flight by the Wright brothers. This milestone in aerospace history calls for both reflection on the past and some speculation about the future of flight. Among the many celebrations of that event was a half-day symposium at the 2003 NAE winter meeting that brought together an extraordinary panel of experts whose presentations gripped the audience that packed the Academy auditorium.

Richard Hallion, former Air Force historian, reminded us that, although the Wrights were first in flight, their lead, our national lead, was almost immediately lost to Europeans; the Wright brothers' design was unstable and difficult to fly, and they were overconfident, unsuccessful businessmen. As Dr. Hallion pointed out, U.S. pilots flew the planes of other countries in World War I. But aided by the migration of skilled Europeans after World War I, the United States regained the lead in 1938.

The futurist, Robert Walker, who led the Commission on the Future of the U.S. Aerospace Industry, gave an unvarnished, visionary, and "high rpm" view of the future. "Anyone, Anything, Anytime, Anywhere" is what people aspire to in twenty-first-century air travel, he told the audience. Mr. Walker envisions nanotube-structured hypersonic aircraft, powered by antimatter, piloted by nanoprocessors, and with access to global positioning networks that will be able to fly anywhere on the globe. These aircraft will be as accessible to the public as general transportation networks are today. That sums up what the twenty-first century will look like in his view.

Innovator **Alan Epstein** of MIT, and an NAE member, reset the scale of useful aircraft downward with examples of 50-gram, 6-inch aircraft today, 2-inch aircraft tomorrow, and possibly even smaller ones later on. Ever think about a 4-mm gas turbine that can deliver 60 watts of power at a few million revolutions per minute? Payloads for these aircraft typically include cameras, sensors, and communication systems, making them useful for security, military, environmental, and commercial applications. Very exciting stuff.

Meyer Benzakein, an engineer from General Electric and NAE member, addressed the topic of propulsion, specifically the progress in gas turbine performance and gas turbines of the future (not included in this issue). He balanced strategies for incremental improvements to current technology with the pursuit of new ideas to push this mature propulsion technology forward. No radically new propulsion system was on his current horizon.

Daniel Mooney, a builder at Boeing, presented the next-generation design for commercial aircraft and discussed innovations in engineering and manufacturing (not included in this issue). And, although much has changed, especially in terms of efficiency, I was reminded that much has stayed the same in the aircraft itself over recent decades. A future in commercial aircraft that differs radically from today was not apparent. This cautiousness, possibly spurred by the pragmatism of a mature industry, contrasted sharply with the inventions of the Wright brothers a century ago and the vision of the next century described by Robert Walker.

Two additional contributions on military aviation are included in this issue. Michael Clarke of the National Research Council Air Force Science and Technology Board and a former pilot addresses innovations and individuals in the history of military aviation. He also makes energetic prognostications about the future. **Harry Hillaker**, program leader of General Dynamics and an NAE member, chronicles the development of the extremely successful F-16 Fighting Falcon.

Considered together, these presentations lay out the national aerospace problem. How do we prepare for the future and at the same time survive commercially today? The Wright brothers failed to solve this problem 100 years ago, but it still has not been solved. The recently announced national agenda to build bases on the moon in preparation for manned flight to Mars heightens the importance of resolving this question and not allowing the United States to fall behind, as we did a century ago.

Much depends on whether we believe aerospace is a mature industry, like newspapers, or a developing industry, like digital technology. Mature industries increment; developing industries innovate. Our nation cannot succeed in aerospace in the next century unless aerospace is a developing industry. New technologies are admittedly expensive, but failing to commit to creating them would be even more expensive. We have no choice if we plan to stay in the aerospace business.

The federal government will continue to play a major role in our aerospace future. As Robert Walker laid it out for the symposium, we need to take on traffic management, infrastructure, business models, aircraft manufacturing, military needs, workforce, nanotechnology, new engines, and hypersonic aircraft. This is a tall, but necessary, order. An inferior position in this industry is not sustainable for our country.

C.D. Mote Jr.

We must commit ourselves to remaining an aerospace nation and to reinvigorating the aerospace industry.

Remembering the Legacy: Highlights of the First 100 Years of Aviation

Richard P. Hallion is a senior advisor to the U.S. Air Force for air and space issues.

Richard P. Hallion

There are many lessons to be learned, both positive and negative, from the first 100 years of flight.[1] On December 17, 1903, Orville Wright completed the world's first powered, sustained, and controlled heavier-than-air flight, covering 120 feet (less than the wingspan of a jetliner) in 12 seconds. Many today believe the myth that the Wrights were "mere" bicycle mechanics who decided on a whim to make the first airplane. In fact, they were well trained by the standards of the day, thoroughly documented everything they did, and were intimately familiar with pioneering work that had gone on before. They first demonstrated their ideas on kites, then moved on to a succession of gliders, regrouped and did significant wind tunnel research, refined their ideas, and finally moved to the 1903 powered machine. The Wrights then built upon their success to improve aircraft, leading to their first successful military machine, the 1909 Flyer.

Decline

But the seeds of their failure as entrepreneurs were already germinating. Not only were they wedded to the marginally stable (at best) "tail-first" configuration, they were also vastly overconfident and curiously reluctant to

[1] The opinions expressed in this paper are those of the author alone and should not be interpreted as representing an official position of the U.S. Department of Defense.

move beyond their original configuration with its modest performance. In addition, very few could fly this airplane as well as they could. By mid-1909, they had become increasingly distracted by emerging rivals, and they launched (not without reason) a series of controversial patent suits that did little but inhibit the growth of America's aircraft industry.

American aviation declined at an alarming rate up to and through the First World War.

Combined with lukewarm government interest, the stage was set for predictable disaster. By 1912, America had fallen behind Europe in aviation; indeed, by mid-1908, before the Wrights had ever flown overseas, the French had developed inherently stable aircraft designs, notably the Farman and the Blériot, that would enjoy greater market success than Wright aircraft. In 1912, French airmen came to the United States and won the Gordon Bennett speed trophy in the Deperdussin Monocoque Racer, without facing any American opposition. In short, Europe was on the road to the streamlined monoplane while America was still in the open-framework, birdcage era.

As American aviation continued to decline at an alarming rate up to and through the First World War, foreign aircraft (such as the Blériot) and design practices and standards (including foreign-derived wing and airfoil shapes) were imported. Indeed, America's best known airplane of the First World War, the Curtiss Jenny, was designed by a British engineer who had been lured to America. Overseas, American airmen flew fighters, bombers, and observation airplanes of French or British or Italian origin. We excelled in only one area—the design of long-range, maritime-patrol flying boats, which led to America's next great international accomplishment in aviation, the first flight across the North Atlantic, by the Navy's NC-4 in 1919.

American indebtedness to Europe persisted after WWI. Our military and civilian workhorse in the 1920s was Britain's ubiquitous De Havilland D.H. 4, a bomber and reconnaissance airplane turned mail plane; and American fighter pilots flew French SPADs and American-built versions of the British S.E. 5 well into the 1920s. In short, our long and painful recovery (which was not foreordained) took more than 25 years, from 1910 to approximately 1938. Bluntly speaking, we benefited from the disastrous economic circumstances and postwar chaos in Europe that prevented the Europeans from taking full advantage of their technical and organizational superiority in aeronautics.

The pervasive European influence on American aviation ranged from technical visits to the United States and exchanges of ideas by prominent technologists to the "brain drain" migration of leading Europeans, foremost among them Max Munk, Theodore von Kármán, Anthony Fokker, and Igor Sikorsky. Exposure to these forward-looking thinkers encouraged American designers to adapt and exploit the latest European structural and aerodynamic practices, exemplified by the wooden (and later all-metal) monocoque structure and the cantilever wood (later metal) wing. In addition, American governmental and academic organizations adopted the European models for aeronautical laboratories and academic institutions. The National Advisory Committee for Aeronautics (deliberately patterned on Britain's Advisory Committee for Aeronautics) rose to research preeminence thanks largely to Munk and his variable-density wind tunnel. The philanthropical largesse of the Daniel Guggenheim Fund for the Promotion of Aeronautics, which established schools of European-style aeronautical engineering across the nation, profoundly influenced the reshaping and redirection of American aviation and facilitated Theodore von Kármán's coming to the United States.

The rapid development of air transport in Europe encouraged federal legislation (especially the Kelly Act of 1925 and the Air Commerce Act of 1926) that stimulated American commercial air transport. Charles Lindbergh's flight to Paris in 1927 generated a healthy "air mindedness" among Americans, that benefited airmail and passenger-carrying services. The broad plains were ideally suited for commercial aviation, which led to the rise of Wichita as the center of America's light aircraft industry. In this supportive climate, designers rapidly exploited advances in streamlining and structures and applied them first to technology demonstrators and then to practical aircraft. Air-racing airplanes, which constituted the "X-series" of this time period, tested developments in engines and aerodynamics and new structural configurations.

Resurgence

By the early 1930s, American air transport aircraft were challenging the dominance of European aircraft. This was dramatically illustrated by a 1934 England-to-Australia air race, when "off-the-shelf" Douglas and Boeing airliners finished a close second and third behind a special-purpose British racer. Both American airplanes reflected the influence of John K. "Jack" Northrop, the most important American designer of his time. Northrop is primarily remembered today for his disappointing (if prescient) work on flying wings, but he was the key individual between the wars in reshaping conventional American aeronautics. His advanced all-metal wing design, which drew heavily on European structural work, set a design standard that was emulated by Boeing, Douglas, Lockheed, and other manufacturers.

By the late 1930s, American airliners (typified by the DC-3) represented the "gold standard" of air transport design. The industry had grown tremendously, and America had become the largest manufacturer and exporter of aircraft in the world. European nations began to buy American airliners, a practice that would continue until the advent of Airbus. Industry in general expanded exponentially to meet growing foreign demand; exports rose almost 70-fold to $627 million in 1941 (roughly equivalent to $7.6 billion today). Exports played a key role in keeping the aircraft industry thriving, even in the midst of the Great Depression; in 1937 exports constituted 34 percent of total American aviation sales.

During the Second World War, America was justly called the "Arsenal of Democracy," and nowhere was that more evident than in the American contribution to Allied airpower. The United States furnished almost 300,000 airplanes to its own and foreign services, more than twice as many as were built by its nearest competitor, the Soviet Union, and nearly 60 percent more than the *combined* wartime production of Nazi Germany, Imperial Japan, and Fascist Italy.

Arguably, this statistic reflects above all the American genius for building a "systems of systems" approach, whether for technology integration, military operations, or the training and organization of combat and industrial forces. The knack for concept refinement, industrial organization, and output could be considered the great strength of American aviation, the "American genius" of the aircraft revolution. Some other nations produced very fine, advanced machines, but overall, the United States produced the best bombers, fighters, transports, trainers, and naval aircraft. Our enemies were overwhelmed by the extent to which we produced easily maintained, high-quality, "user-friendly" aircraft literally by the thousands. For example, neither friend nor foe produced a single long-range bomber equal to any of the four bombers we fielded in combat—the B-17, B-24, B-29 and B-32.

We emerged from WWII, as we had from WWI, as the dominant global economic power, a nation essentially untouched by the destructiveness of war (save for the human losses and suffering of our soldiers, sailors, and airmen and their families) with a robust, vigorous aeronautical industry. From the standpoint of prototyping and production, the postwar years were a "Golden Age" for American aviation. We adapted to the jet age, pioneered transonic and supersonic flight, and continued to increase our dominance in the field of international air transport. By the mid-1970s, American aviation was in a dominant position in many fields, and research was under way that promised to continue that trend into the 1980s and beyond. Our new military aircraft were at least a generation, and sometimes two, ahead of any adversary's aircraft, and would prove their worth in the conflicts of the 1990s. Our airliners—particularly the 747—reshaped international air commerce. Our general aviation industry was producing upwards of 17,000 airplanes per year and selling them around the globe. And in space, we landed teams of astronauts on the moon, setting the stage for the post-Apollo space program.

The postwar years were a "Golden Age" for American aviation.

To recap, then, America invented the airplane in 1903, allowed other nations to get well ahead, and then spent a quarter-century catching up before we secured, once again, the dominant place in international aeronautics. Could this pattern be repeated? Well, actually, it was! We have been "scooped" many times, even when, as with the Wrights, we did the pioneering work in a technology field. For example, we did not pioneer radar, liquid-fuel rockets, ballistic and cruise missiles, precision air weapons, the turbojet engine, the jet fighter/bomber/airliner, the swept-wing (which forced hasty redesign of the B-47 and F-86), Earth satellites, or the human presence in space. These scoops didn't merely cause us national embarrassment (Sputnik being the most infamous example), they also endangered our national security.

Indeed, we arguably benefited after World War II, just as we did after World War I, from our raw economic power and an industrial base untouched by war. In the short-term, other nations were unable to maintain their dominance in turbojet propulsion and high-speed aerodynamics. Thus, we were able to "catch up" rapidly and forge ahead, even though being a "fast second" is not an ideal way to operate.

The Centennial of Flight Report Card

In November 2002, the Commission on the Future of the United States Aerospace Industry, chaired by former Representative Robert Walker and former Secretary of the Air Force F. Whitten Peters, warned that "We stand dangerously close to squandering the advantage bequeathed to us by prior generations of aerospace leaders. We must reverse this trend and march steadily towards rebuilding the industry. The time for action is now."

Ironically, as we celebrate the one-hundredth anniversary of Kitty Hawk, we must concede that there has been a truly appalling decline in American aeronautics over the last quarter-century—since, equally ironically, we opened the National Air and Space Museum with much fanfare in 1976. When we ask ourselves a basic and very uncomfortable question—how we have done as stewards of the aerospace health of this country—the answer is not very well.

What we have lost over the last 25 years calls down serious judgment upon our national aeronautical and space research and development establishment, including the government, corporate, and academic communities. We often say studying the past informs the decisions of the future, but, in truth, it rarely does. Rigorous assessments of aerospace—where we've been, where we are, and where we're going—have been rare. (One notable and welcome exception was the Air Force's *New World Vistas* study in 1995, which was launched by then-Secretary of the Air Force Sheila Widnall and chaired by Gene McCall of the Scientific Advisory Board.) Examples of changes in American aerospace can shed some light on the challenges confronting us today.

From a VJ-Day high of 47 major airplane manufacturers, we have winnowed down the field to five. Industry employment has plummeted by nearly 50 percent (611,000 fewer workers) since the end of the Cold War. Twenty-six percent of the remaining workforce of 689,000 will be eligible for retirement in the next five years.

Our investment in aeronautical research continues to decline (50 percent since 1987). In addition, the number of American students studying air and space subjects in colleges and universities has decreased nearly 60 percent since 1990.

Our general aviation industry has essentially been destroyed (Figure 1), largely as a result of frivolous lawsuits, and is only now very slowly recovering, thanks to the General Aviation Recovery Act (GARA). Some product lines and firms have disappeared or (like Learjet) been acquired by foreign companies.

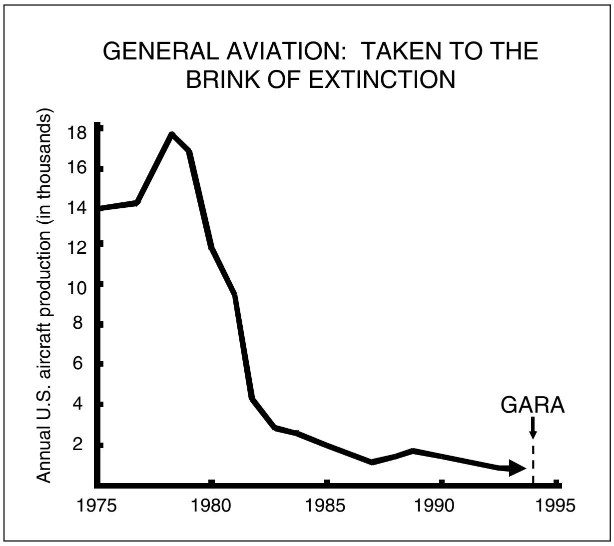

FIGURE 1 The precipitous decline of U.S. general aviation. Data courtesy of Wen Painter.

American market dominance in global air transport has disappeared, for the first time since the advent of the practical airliner. Of the top four manufacturers of airliners, only one, Boeing, is American; the other three are Airbus (European), Embraer (Brazilian), and Bombardier (Canadian). American dominance in commercial helicopters, once taken for granted, has also evaporated in the face of innovative design and marketing by foreign partnerships.

Our once-unquestioned dominance in space has declined as well. U.S. commercial space exports have fallen 75 percent in just three years. In 2002, only 14 percent of the engines flown into space were American built. Eighteen percent came from Europe, and 61 percent from the former Soviet Union; the rest came from Asia. Our space capabilities are still largely rooted in the derivatives of first-generation ICBMs and IRBMs, one of which (the Atlas III) has recently been redesigned to use Russian engines.

Undoubtedly it would surprise the public, after a decade of well publicized military triumphs, to learn that our traditional dominance in military aviation has also been eroded. If our military airplanes were automobiles, most of them would bear classic car plates. Consequently, we are facing serious safety issues, ranging from potentially catastrophic structural failures to wide-area metal corrosion—sort of an aerospace osteoporosis. Our fighters—the F-14, F-15, F-16, F/A-18, A-10, and AV-8—have all been flying for more than a quarter-century. In theory, and perhaps now in fact, a fighter pilot could be "pulling g's" in a fighter that was manufactured and flying before he or she was born. Crew members of bombers and tankers could be—and perhaps in some cases are—the grandchildren of the original crew members. Even the stealth fighter, the F-117, entered operational service 20 years ago, in October 1983.

Disturbingly, American air dominance, the sine qua non of our combat operations, is no longer a given. In February 2003, Secretary of the Air Force James G. Roche and Air Force Chief of Staff General John P. Jumper warned of a growing performance gap between older American fighter planes and newer foreign fighter planes. "Our guy flying their airplane beats our guy flying our airplane every single time," General Jumper noted; Secretary Roche affirmed that, in one case, we were dependent solely upon "the advantage provided by our extraordinary pilots." This is a worrisome situation we have not seen since before Pearl Harbor.

Beginning in 2010, as the "baby boomer" generation ages, outlays for age and retirement-related expenses will rise dramatically, together with other obligations, such as interest on the national debt. Unlike discretionary spending, which is optional, these costs will have to be paid. We are purchasing today the production capabilities for tomorrow's multiyear modernization of both military and civilian aerospace; but, once the crisis hits, it is questionable if we will actually have the money we need for these systems, either for aircraft, like the F/A-22, the F-35 Joint Strike Fighter, uninhabited aerial vehicles (UAVs), and new helicopter and vertical/short takeoff and landing (V/STOL) aircraft, or for new systems, such as hypersonics and reusable and reliable space-lift vehicles. Personally, I don't think we will; indeed, the F/A-22 Raptor and the F-35 Joint Strike Fighter have already experienced significant delays and reductions in procurement. The coming crunch will force us to make very difficult choices over the next seven years just to adjust to the challenging research, development, and acquisition world we will face after 2010. But we do have a grace period of a few years to prepare, if we are prudent enough to take advantage of it.

Faced with declining enrollments, many schools are closing engineering schools.

The greatest challenge of all, however, is not declining market share, competitiveness, and military dominance, or even economics. The biggest challenge is mind-set. We must excite our youth about the air and space field, particularly to the challenges ahead. It was "air mindedness" that offset the dreadful decline in American aviation after the Wrights, and it was "aerospace mindedness" that offset the dramatic impact of Sputnik nearly four decades later. But students today are increasingly opting to study life sciences, a result, at least partly, of four decades of proselytizing in elementary and secondary schools. Faced with declining enrollments, many schools are closing engineering laboratories, even as they build life sciences laboratories.

Our Future as "An Aerospace Nation"

If we fail to attract dedicated young people, the aerospace industry will not have an American future, and our repeated claims of being "an aerospace nation" will ring increasingly hollow and false. We must excite our young people with new concepts that take us beyond the tired solutions of the past. We must be willing to shatter existing paradigms and patterns, whether the primacy of the "tube-and-wing" airliner or the notion that we have reached a plateau on speed. Why shouldn't we challenge ourselves to go beyond the transonic? Since the Industrial Revolution, the history of mass mobility has been a history of increasing speed: the animal-pulled cart, the locomotive, the airplane: 6 mph in 1800, 60 mph in 1900, 600 mph in 2000. Might we not expect 6,000 mph in 2100? At the very least, we must explore the promise of a blended wing-body transport, an ocean-crossing supersonic business jet, and then a genuine, hypersonic, globe-girdling transport.

Some will argue that there is "no need" for these aircraft, no "customer demand," that "we can't afford to bet the company," that these ideas are "too revolutionary," much the way critics once argued against airliners in favor of long-distance trains. In response, we might note, as W. Edwards Deming famously said, that no one ever asked for the light bulb or the pneumatic tire, the steam engine, the locomotive, the airplane, the PC, etc. Certainly, there was no defined need for a global air transport system when the Wrights invented the airplane; had they advanced such an idea, even after Kitty Hawk, many would have thought them mad. The American aviation industry predominated because now-legendary figures, such as Jack Northrop, Igor Sikorsky, Donald Douglas, Walter Beech, Bill Allen, and many others, were willing to bet their companies and did so more than once.

Let us at least have the fortitude to explore some of the alternatives to today's aircraft, including new and more efficient subsonic general aviation and air transport

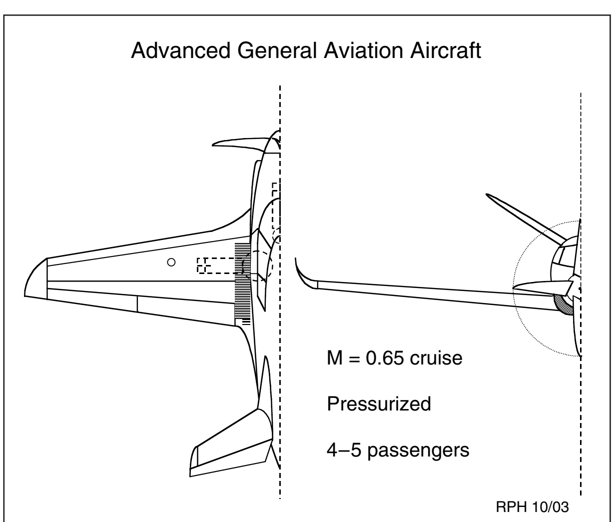

FIGURE 2 Advanced general aviation aircraft.

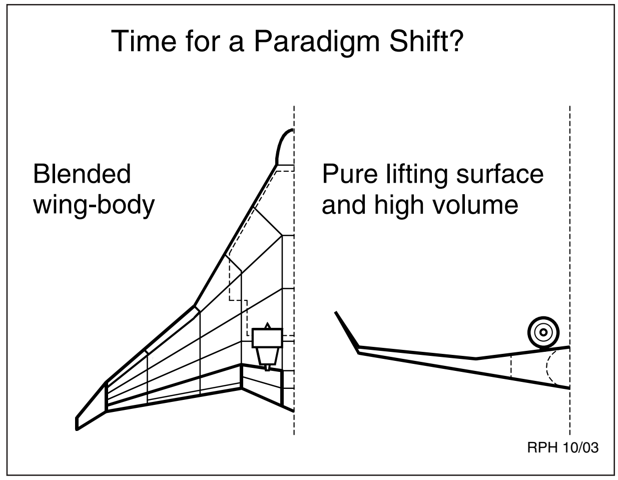

FIGURE 3 Blended wing-body transport concept.

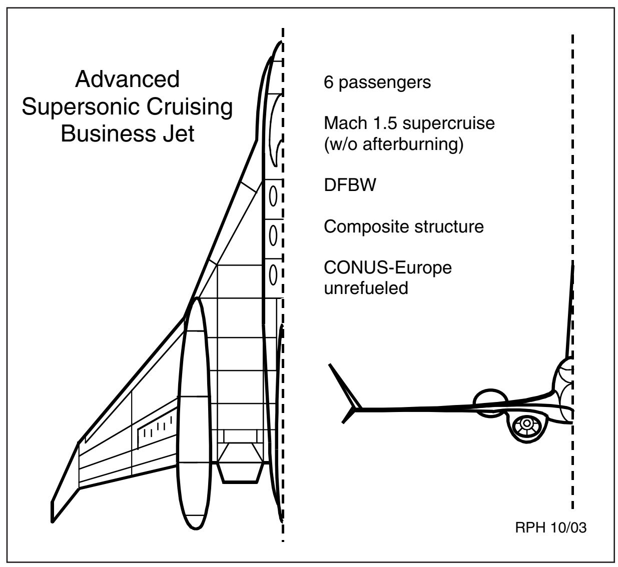

FIGURE 4 Supersonic cruise business jet.

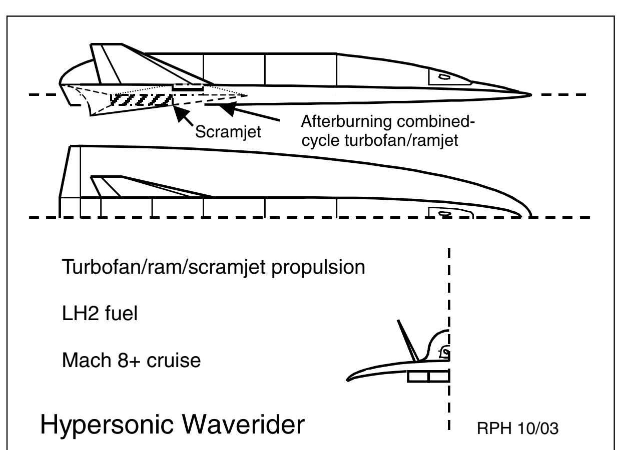

FIGURE 5 Mach 8+ hypersonic research aircraft.

airplanes (particularly blended wing-body designs), supersonic business jets (and possibly larger follow-ons), and hypersonic demonstrators that might extend the "6-60-600" rule to Mach 8 or 9 by the turn of the next century (Figures 2-5). And if some believe these are "too revolutionary," let us remember, in the words of Dr. Gene McCall and Maj. Gen. John Corder in the *New World Vistas* study, "Most revolutionary ideas will be opposed by a majority of decision makers."

To echo the final report of the Commission on the Future of the U.S. Aerospace Industry, the time for action is now. On this anniversary, we should affirm our commitment to remaining an aerospace nation and to reinvigorating an industry that is vital to our future. The best way to honor the Wrights and all of those who revolutionized the world through the air is by pushing ahead—and by ensuring that we do not repeat the mistakes and misjudgments of the past.

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Technology development in hypersonics could remap the future.

Building on the Legacy: A Vision for the Future

The Honorable Robert S. Walker is chairman of Wexler & Walker Public Policy Associates in Washington, D.C.

Robert S. Walker

At the opening session of the Commission of the Future on the United States Aerospace Industry (the Aerospace Commission), I quoted Wilbur Wright who once opined that mankind would not achieve flight "for a thousand years." This was just a year before he and Orville achieved powered flight. So much for predicting the future in aerospace! Wilbur was wrong about their timetable, but, when it comes to technology, it is difficult to predict where you are going based on where you are.

We do know that the history of aeronautics and flight has been a history of progress and success achieved by the integration of technologies that are either coming of age or still in the laboratory. The Wright brothers' success was based on integration of the internal combustion engine, a rather new technology at the time, with the control of wing surfaces. Prior to the invention of the internal combustion engine, power sources were too heavy for an airplane. Thus, the integration of internal combustion and aeronautics began a century of flight.

Throughout the twentieth century, aviation advancement depended on the continuous adaptation of new technologies into the field. As breakthroughs occurred in propulsion, aerodynamics, and materials, they found their way into new generations of aircraft. Based on what is going on in laboratories today and where technology breakthroughs are aiming, we can make some educated speculations about the future of aviation.

Technology development in hypersonics could remap the future. The U.S. Department of Defense (DOD) has launched the National Aerospace Initiative as part of the Defense Research and Engineering Program. Work on hypersonics will focus on propulsion technologies and new fuels for aviation, such as hydrogen, which has been used extensively as a fuel in the space program but only experimentally in aviation. As scientists work toward the creation of high-speed vehicles, hydrogen could be the fuel of choice. And, of course, hydrogen is also being investigated to meet a variety of other energy needs.

Propulsion technology has not advanced very far in the past half-century. A robust hypersonic program will involve a reappraisal of supersonic ramjet engines (scramjets); in fact, some of our international competitors are already conducting interesting tests in this area. A predictable outcome of a hypersonic program is another look at aerospike engines, which were developed to power the X33. One of the great disappointments in recent aviation history was the failure to flight test the X33 after it was 85 to 90 percent complete. Under pressure from supporters of the space shuttle, the National Aeronautics and Space Administration (NASA) cancelled the program, thus passing up an opportunity to flight test a new generation of engines that had proven to be quite capable in stationary tests.

Hypersonics will also involve advanced aerodynamics. Today, sonic boom creates an environmental and quality-of-life hurdle for high-speed travel. Work is under way on new designs to reduce sonic boom, which would open the way to hypersonic aircraft. Thus, research on hypersonics could lead to new developments in propulsion, materials, fuels, and design. But that may be only the beginning. Information systems, for example, will also be important for the development of new aircraft designs, as well as for avionics and flight control. The air traffic control system of the future will rely upon advanced, space-based information regimes and the capability of spectrum compression.

If we look farther down the road, advanced experimentation in the nation's laboratories reveals even more exciting possibilities. Work on antimatter being done at Pennsylvania State University and elsewhere could lead to completely new propulsion capabilities in this century. Some scientists also are seriously considering gravity management. Antimatter and gravity management could potentially lead to an aerospace future of unimaginable proportions.

The Aerospace Commission was chartered to consider potentials beyond technological advances. We were also asked to look at the aviation marketplace, with a focus on current developments as a basis for predicting changes in the future. Our conclusions are reflected in the title of our report, *Anyone, Anything, Anytime, Anywhere*.

We identified one overwhelming desire for military and civil aviation—people want to be moved quickly, exactly where they want to go and when they want to go. Defense planners want to be able to move people and munitions quickly wherever they are needed in an emergency. Commercial aviation aspires to move people and goods to specific destinations in as little time as possible. Aerospace assets are the best way of fulfilling everyone's dream of anyone, anything, anytime, anywhere.

The global marketplace will demand increasing individualization and customization in air transportation.

The global marketplace of the future is going to demand increasing individualization and customization. For the aviation industry, which has relied heavily on mass production and mass movement, the new marketplace will present many challenges. The high-end traveler of the future is not going to be satisfied to be shuffled from hub to hub before getting to his or her final destination. High-end travelers will want to fly directly to their destination at their convenience. Military planners will want the ability to strike almost instantaneously anywhere in the world, and they will need new generations of aircraft with that capability. Technology must be developed to meet the needs of civilian and military aviation.

On the civilian side, the Aerospace Commission focused on the concept of air taxis. A small innovative company, Eclipse Aviation, described its development of reasonably priced jet aircraft designed to become the backbone of an air-taxi service. This concept is consonant with our conclusion that the demand for individualized travel will certainly increase. With air taxis, a businessman or woman would call for service, be picked up at a large or small airport of his or her choosing, and be delivered to the exact destination at the most convenient time. The system would operate on a regional basis at first, for a cost of about one dollar per mile. The need for air-taxi service is already apparent. With the present system, door-to-door flight time on trips of 500 miles or less averages 35 to 80 miles per hour.

Another development likely to have implications for the marketplace is unmanned aircraft, which have already had an impact on military aviation. Unmanned aircraft proved their worth during the conflict in Iraq, but also revealed the need for improvements. An enormous amount of spectrum was required to fly unmanned missions in Iraq. This experience has shown that the widespread adoption of unmanned technology will require more work on spectrum compression and other applications of information technology.

The economics of the marketplace will drive us toward more unmanned capabilities. In the future one can imagine freight being flown largely by unmanned aircraft. Once vehicles and systems are capable of handling planes without pilots, it will make little sense to fly them with pilots.

The economics of the marketplace will drive us toward more unmanned capabilities.

It may take longer for passengers to fly on pilotless airplanes, but in the course of this century that is also likely. Remember that not too long ago every elevator had a human operator, partly for safety and security. Today we think nothing of putting our safety in the hands of an automatic elevator (except in the Capitol, where elevators still have human operators). Once a safe, secure, robust air traffic management system has been developed, it is not hard to imagine that people will elect to fly aboard pilotless aircraft.

The expanding global economy will also affect the future of aviation. The products we rely upon will no longer be manufactured just down the road or just across the border in a neighboring state. These products will come from all reaches of the globe, as many already do, and as more and more speed of delivery is required, aircraft will become the supply line. In general, the reliance on aircraft to move people, goods, and services around the world will become more pronounced. The global economy will also mean growing competition. Many countries can be expected to make some aspect of aerospace a national priority. We have already seen fiercely competitive commercial operations in space and aviation.

When you look outward, you begin to get a glimpse of a future that may look like this: individualized travel on hypersonic aircraft built of carbon nanotube structures, piloted by nanoprocessors accessing a global guidance network, flying into every locality, powered by antimatter engines, and as accessible to everyone as the transportation system today. This scenario will probably be realized well down the road, but if you think back to the technological growth of the past 100 years, the scenario is well within the realm of possibility. In fact, everything in it is already the subject of laboratory work.

The real question is what policy makers should be doing now. The Aerospace Commission came to the unanimous conclusion that the most important thing is the development of policies that enable us to move toward this exciting future. One priority should be the development of an advanced air traffic management system. The current antiquated system is not capable of handling future demands, and continued dependence on voice communications from ground controllers to aircraft cockpits is untenable. We need to focus on technologies that permit fairly automated, more robust, more secure aircraft control within airspace. Such a system could be adapted from advanced technologies already known to us, which could be accessed without massive cost by using the global satellite constellations being developed by DOD.

The command, control, and navigation satellites under development for military applications could be adapted for civilian use, much the way the global positioning system (GPS) constellation has been adapted to meet civilian objectives. This would greatly reduce the tremendous expense usually associated with the development of an automated air traffic control regime. Even the costs of including civilian components on military spacecraft could be mitigated by interagency cooperation. The nation would acquire a spaced-based system with upgraded ground control elements. The military would fly the space-based hardware, but ground-based operations would be in the hands of the Federal Aviation Administration (FAA). The result would be that the nation would have the advanced air traffic management system necessary for the United States to compete in the global economy and to meet national security requirements.

Since the Aerospace Commission made this recommendation, considerable progress has been made. DOD, the FAA, and NASA have joined a working group to create the system. No doubt, bureaucratic, cultural, and funding issues will have to be resolved, but the first steps are being taken.

Another imperative for the future is a significant improvement in infrastructure beyond air traffic control. One of the most revealing figures we heard was that in the United States commercial flights of 500 miles or less have an average door-to-door speed of 35 to 80 miles per hour. That figure reflects serious problems with infrastructure. Clearly, one way to improve infrastructure is to restructure the airlines. We cannot have a robust aviation system if airlines cannot afford to purchase aircraft, if a significant number of airlines is on the verge of bankruptcy, and if airline business plans do not work because more and more high-end customers, who used to fly in the front of airplanes and pay a substantial portion of the cost, are traveling on charter aircraft. In the future, even more of them will opt to fly by air taxi.

The customers left to airlines are becoming largely vacationers, who want very low prices. Coming up with a profitable business model based on low fares is tricky; at the least, it requires substantial restructuring of old labor agreements. But much more will have to change, including mergers with international airlines and much more customized travel. Aircraft manufacturing will have to be highly productive, thus relying much more on robotics. The military must be able to project power rapidly and decisively using hypersonic weaponry that cuts the time of mission success from hours to minutes. There must be much more interagency planning and policy implementation so that the vast sums of money spent for aerospace are allocated rationally according to broadly determined priorities. Congress must take the "stovepipes" out of the appropriations process so that duplicative spending does not deplete financial resources.

In the future, our export control policy must allow our aerospace industry to compete globally rather than erect barriers to overseas contracts; of course, some technology products must be protected, but the technologies that really do require protection would be more secure if the government were more selective in deciding which products need individual munitions licenses. Government procurement polices must promote growth and the long-term stability of the aerospace industry. Our society must be scientifically and technologically literate, and our educational system must produce the trained workforce we need in aerospace.

One way to improve infrastructure is to restructure the airlines.

Finally, we must invest more in research so that we can achieve breakthrough capabilities and develop new knowledge. In my years on Capitol Hill, I became convinced that the basis for national economic strength and global economic leadership is remaining on the cutting edge of the development of new knowledge. Peoples and nations that are prepared to launch voyages of discovery on earth and in space will dominate this century economically, culturally, politically, and militarily.

Our legacy as a nation in aerospace is to lead, not to follow. The costs of being a follower have been great, so lead we must. Today, our claim to leadership is being challenged on many fronts. The Europeans, Brazilians, and Canadians are on the move in the arena of commercial aircraft. In human space flight, the Chinese have put a man in orbit and announced plans to be on the moon within six years. The Europeans intend to use the Galileo program to leapfrog us in air traffic management. The Russians have tremendous capabilities in robust rocketry.

The Aerospace Commission set forth certain requirements for the United States to retain its leadership in aerospace during this century:

- We must build an entirely new air traffic management infrastructure that relies on automated systems and communicates directly with information systems in every aircraft.

- We must create strong, lightweight, composite aircraft structures with smaller, quieter, lighter weight engines, so we can build airplanes that are relatively inexpensive to buy and to operate.
- We must make aircraft that are good neighbors where they take off and land, so that airports are economic assets rather than community burdens; thus, aircraft must have quieter engines and environmentally friendly operations.
- We must give people the same sense of confidence in boarding an airplane without a pilot, as they have when they step into an elevator without an operator.
- We must think of our space program as a legacy of exploration calls forth our courage, inspires our imagination, and leads to new knowledge and new understanding, and, therefore merits our investment.
- We must create propulsion technologies that allow us to conduct voyages in the solar system in a politically acceptable time frame, so that their accomplishment becomes a political imperative.
- We must be prepared to accept the risks, as well as the rewards of exploration, particularly the exploration of the most hostile environment ever faced by humankind.
- We must be aware that, if we do not choose to lead in the exploration and exploitation of air and space, others will; the ability to move people, goods, and munitions anywhere at any time is the formula for global dominance in this century.

We have been given an opportunity and a challenge—to address the needs, meet the challenges, and move aerospace at least as far forward in this century as our fathers and grandfathers did in the last century. When the Wright brothers gave humans their wings, they extended not only the capability of the human body, but also the capability of the human mind. They extended our vision and our dreams. For some that meant the opportunity to visit distant lands, for others to dream of visiting distant worlds. We are different today than we were 100 years ago because we can fly and because what was once a miracle has become routine. We will be different 100 years from now because humans will populate the heavens. Flight will continue to inspire the imagination. By daring to fly in air and space, we reach to touch the face of creation. When we look up, we see the destiny of mankind and the destiny of America. When we look up, we also look ahead—to a new century of flight.

Once aircraft no longer required human operators, they could be made much smaller.

The Role of Size in the Future of Aeronautics

Alan H. Epstein

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Since the first controlled powered flight by the Wright brothers 100 years ago, aircraft size and range have been important measures of progress in aviation. Large payloads have always required large aircraft (although the definition of large has evolved over time). In the early days of aviation, the fuel capacity required for long-range flight also dictated large size; thus, size and range were coupled. The first aircraft sold by the Wright brothers in 1909 to the U.S. government, the Wright B Flyer, had a 40-foot wing span, a takeoff weight of 1,400 pounds, a range of 90 miles, and required a pilot and an observer. In terms of payload and range, the B Flyer was a state-of-the-art airplane.

Ten years later, the first aircraft to cross the Atlantic Ocean, the Navy-Curtiss NC-4, had a wingspan of 126 feet, a crew of six, and a takeoff weight of 27,000 pounds (Figure 1). This airplane was designed by NAE member Jerome Hunsaker. Because the NC-4 had a range of only 1,400 miles flying at 75 miles per hour, it had to be refueled along the way. By the time of Lindbergh's solo nonstop transatlantic flight in 1927, aeronautical technology had progressed to the point that an aircraft with a wingspan of 46 feet and weighing only 5,100 pounds could fly nonstop 3,600 miles from New York to Paris. In one sense, the Lindbergh airplane had an optimal design—the flight control, navigation, and payload were embodied in one person. Twelve years passed before the next transatlantic milestone, the

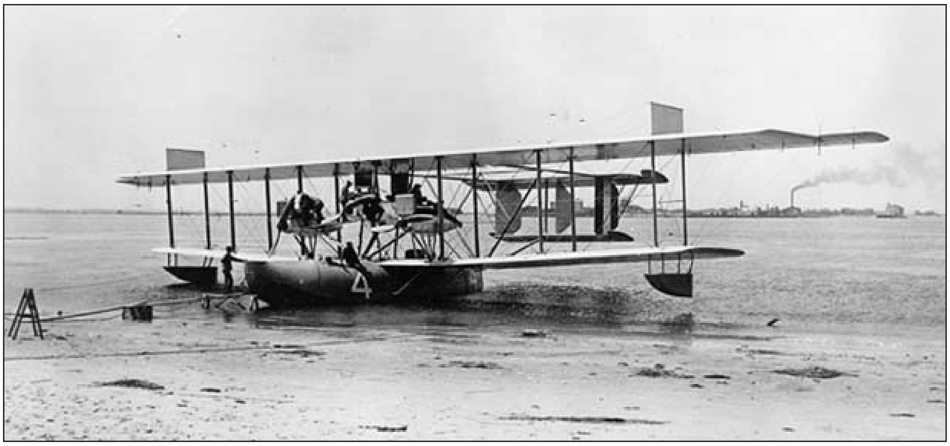

FIGURE 1 The NC-4, the first aircraft to fly across the Atlantic. Reprinted courtesy of MIT Museum.

start of scheduled commercial service in 1939 by the 84,000 pound Boeing Model 314 Clipper with a 152-foot span and a nominal range of 5,200 miles at 184 miles per hour. By this time, large size was dictated as much by commercial considerations (basically seat mile cost) as by technical considerations. Commercial considerations continued to dictate the size of aircraft throughout the jet era.

Eighty-four years after the Wright brothers' flight, technology had advanced sufficiently that the Aerosonde, a model airplane with a 10-foot span and weighing about 30 pounds, could cross the Atlantic. Lindbergh's heroic, lone pilot was replaced by inexpensive avionics, a microprocessor, and a satellite navigation receiver. Like the NC-4, the Aerosonde cruised at about 75 miles per hour. In 2003, the even smaller TAM-5, a model airplane weighing just 11 pounds, made a similar transatlantic flight. In contrast to this smallest transoceanic flyer, we now have commercial aircraft weighing more than a million pounds with transpacific range. Thus, by the end of the first century of flight, the connection between aircraft range and size that had been so important in the early years of aviation had been broken.

In military aircraft, range and size have been important historically, but military planners now focus on achieving effects, such as destroying a building. Figure 2 presents a historical perspective of the number of sorties (one flight by one aircraft) flown to ensure a hit on a 60-by-100 foot building. In World War II, B-17s flew more than 3,000 sorties. A B-17 required an aircrew of 10 and at least that many in the ground crew, so more than 60,000 people were involved, a true army of the air. By the time of the Vietnam War, only 44 sorties were required to hit a 60-by-100 foot building. In the latest Iraq war, only one was required. So the 750,000 tons that took flight in 1944 were reduced by a factor of 30,000 to 25 tons.

Because the number of aircraft on a mission cannot be reduced below one, further reductions in aerial mass for military missions must be in aircraft size. The bombers I just discussed all had gross takeoff weights of about 50,000 pounds. How large must an aircraft be to get the job done? Consider, for example, the task of destroying a well defended target, such as a bridge. In 1972, this was typically done with F-4 Phantoms, an expensive proposition given the inaccuracy of unguided bombs and aircraft loss rates. One contemporary analysis put the price at $12 to $15 million, not including the cost of necessary "extras," such as combat air patrols, tankers, and defense suppression, which together formed a typical "strike package" of 12 to 24 aircraft. In the 1991 Gulf War, two cruise missiles with a range comparable to that of an F-4 (without refueling) could accomplish the same job for about $2 million. In 1972, more than a million pounds of aircraft left the runway at the beginning of a mission; 25 years later only 4,000 pounds were needed, a 25-fold reduction in gross weight and a 10-fold decrease in cost, not to mention the value of the lives that were saved.

Uninhabited Air Vehicles

These dramatic decreases in vehicle size and mission cost were principally enabled by the microelectronics revolution, which reduced avionics mass while providing real-time computation, navigation, electro-optics, and autonomy that greatly improved the accuracy of weapons and so reduced the mass of the weapons required. Perhaps most important, microelectronics have enabled the elimination of people from aircraft, thereby removing an important limitation to shrinking aircraft size.

Uninhabited (and largely autonomous) air vehicles (UAVs) are the latest innovation in military aircraft. Although the concept of UAVs, and examples of limited utility, have been around for more than 50 years, advanced avionics have enabled highly capable UAVs only in the last decade. The value of the UAVs used in recent conflicts has been acknowledged by the operational community. The largest of the current vehicles is Global Hawk, a high-flying reconnaissance aircraft weighing about 25,000 pounds with the wingspan of a small airliner. Global Hawk has a demonstrated transpacific range and endurances of longer than 24 hours. Its smaller and perhaps better known cousin, Predator, is the size of a light plane. In the war in Afghanistan, Predator became the first UAV to fire weapons in combat. The concept of uninhabited fighter and bomber aircraft is being advanced in flight testing of the X-45 and X-46 uninhabited combat air vehicles (UCAVs).

In the Iraq conflict, a host of smaller UAVs have been fielded, some weighing as little as 5 to 10 pounds; these include Pointer, Dragon Eye, and Desert Hawk. These small UAVs are flown by teams of a few soldiers for local reconnaissance or base security surveillance. As a historical footnote, these model airplane-sized UAVs sell for about $25,000, the same price the Wright brothers charged the U.S. government for its first airplane.

Jane's All the World's Aircraft is an 800-page annual compendium of airplanes currently produced and used around the world. The popularity of UAVs can be judged by the size of *Janes' Unmanned Aerial Vehicles and Targets*, which is just as thick. The primary attraction of smaller UAVs is their low cost compared to the cost of manned aircraft. For this reason, UAVs are being embraced by operators, even though they may have less capability than the more expensive manned systems they replace.

The low price of UAVs may eventually alter the business landscape of military aviation. Because of the low development cost of small UAVs, new, small companies can and are entering the market, resulting in a proliferation of offerings. In contrast, current large aerospace concerns are organized to produce $100-million airplanes in $100-billion programs. If large manned programs are displaced by low-cost UAVs, large companies will find themselves challenged to establish viable business models for systems that cost only a few tens of thousands of dollars. Military combat pilots also feel threatened as it seems increasingly likely that no new manned combat aircraft will be in production by midcentury.

As military aviation transitions to and gains experience with UAV operations, it is also increasingly plausible that unpiloted flight will move into the commercial air transport arena. Routine transport flights are no more challenging than combat missions in terms of decision making and autonomy, so that it is reasonable to extrapolate that in the not too distant future, routine commercial flights could be automated. But what about nonroutine events and emergencies? It is true that pilots with extraordinary skills have saved severely damaged aircraft. But less skilled pilots are responsible for the majority of aviation accidents.

In the history of commercial jet aviation, about 70 percent of accidents have involved crew error. As aircraft have become more mechanically reliable, one category of error, controlled flight into terrain (the pilot literally flying an airworthy airplane into the ground because of a lack of situational awareness) has become the leading single cause of fatal accidents. Crew error implies that appropriate, established procedures were not followed. Thus, automation may not have to be as flexible as the very best pilots in all possible situations to maintain current standards of air safety, or

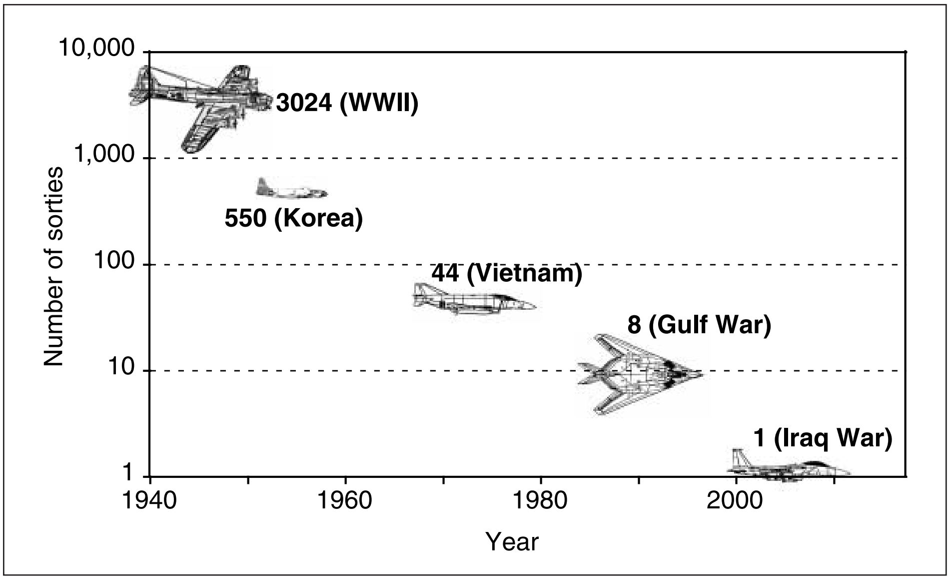

FIGURE 2 The number of sorties required to destroy a 60-by-100 foot building. Source: Brzezinski, 2003.

even to improve upon them. Automated controls that do nothing more (or less) than reliably "follow the book" may result in a safer air fleet on average than we have now.

Automated controls that "follow the book" may result in a safer air fleet.

Technical issues aside, civil aviation may be harder to change than military aviation. Labor is a major issue in civil aviation, and it is difficult to imagine that pilot unions will look kindly on automated transports. Perhaps only new organizations that do not have such stakeholders will be able to deploy the new technology.

Once automated transport airplanes are ready to go, will anyone dare to board them? Probably not without a significant experience base in air cargo or military operations and strong additional inducements, such as low fares. Indeed, the last few decades of air travel suggest that the traveling public values low fares above all else.

At the start of the second century of flight, it is appropriate to ask how large an airplane need be. Aircraft exist mainly for transportation—of people, freight, sensors, ordinance, etc. We can classify missions as either mass specific (carrying things by the pound, such as freight or people) or function specific (accomplishing a task, such as reconnaissance, air superiority, or ground attack). The payload for a mass-specific mission is fixed by assumption (although in many cases the payload could be divided among several vehicles if that proved advantageous). In contrast, the payload mass for a function-specific mission is not fixed. It is determined by payload physics, contemporary technology, and the level of investment.

How small can a payload be? Take the example of destroying a bridge. Given the accuracy of current weapons (10 meters or less), perhaps 500 to 1,000 kilograms of explosives are required. But the minimum explosive mass required to destroy a bridge might be the mass carried by a human sapper who places a few charges at key locations, no more than 10 to 100 kilograms. With advances in explosives and warhead design, the amount might be reduced even further. A sufficiently capable group of future small air vehicles could deliver their payload right to the critical spots, flying under the bridge if necessary, and accomplish the mission with one-tenth to one-hundredth the total payload required by current guided weapons. This implies that the vehicles might be an order of magnitude or more smaller than today's guided weapons for many targets.

Another example is a visual reconnaissance mission. Thirty years ago a payload consisting of a television camera and microwave downlink weighed about 100 kilograms and was carried on a remotely piloted vehicle with a takeoff weight of 1,000 kilograms. That same payload functionality can be realized today in a gram or two. Thus, the vehicle required to carry a payload that can accomplish the same mission could weigh no more than 50 to 100 grams.

Microair Vehicles

Based on this idea, the Defense Advanced Research Projects Agency (DARPA) initiated a microair vehicle (MAV) program in the late 1990s. DARPA somewhat arbitrarily defined an MAV as an air vehicle measuring 6 inches or less in every dimension. The concept is traceable to a Rand Corporation workshop in 1992 (Hundley and Gritton, 1992) that was developed in depth at the Massachusetts Institute of Technology Lincoln Laboratory (Davis et al., 1996). One of the most successful aircraft developed in this program was the AeroVironment Black Widow shown in Figure 3 (Grasmeyer and Keenon, 2001). With a 6-inch wing span and a 56-gram mass, it can fly for nearly 30 minutes

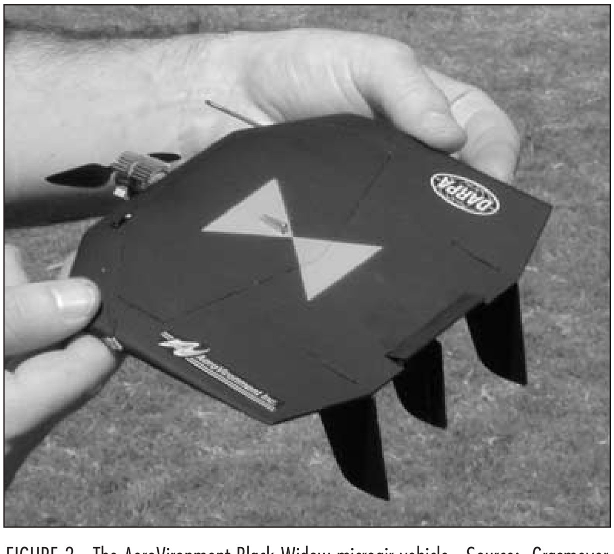

FIGURE 3 The AeroVironment Black Widow microair vehicle. Source: Grasmeyer and Keenon, 2003.

on high-performance batteries and broadcast color video images from a distance of 2 kilometers. The Black Widow was a capable flyer, but it was subject to a hazard peculiar to very small, quiet air vehicles—bird attacks. For large aircraft, such problems have largely been limited to 1950s horror movies.

The DARPA program was a great learning experience for both the technical and operational communities. The technical community discovered that the 6-inch size was right at the edge of the state of the art at the time. Some aspects of the 6-inch airplane came out as expected. Aerodynamics at this scale could be readily calculated so that the poor performance relative to large airplanes (lift-to-drag ratios of 3 to 6 rather than 15 to 20) was no surprise. Instruments for navigation and control (such as 6-gram GPS receivers and 1-gram gyroscopes) were commercially available.

Designing subsystems that did not exist at this scale was more difficult. Propulsion and power systems were two of the most vexing problems. The smallest model airplane engine is ten times too large for a 6-inch airplane that needs about 2 watts of flight power to cruise at 15 meters per second. Battery propulsion had the advantages of low noise and availability, but the best commercial batteries store 25 percent less energy per unit mass than the jet fuel used by a modern gas turbine engine. The energy storage problem was exacerbated by the relatively low volume of a small airplane. Poor aerodynamics combined with limited energy storage space resulted in short flight times, tens of minutes at best. Low transmit powers and small antennas limited radio communications to a range of 2 to 4 kilometers.

Stability and control systems proved to be challenging as well. These airplanes were first flown by remote control rather than autonomously, but the dynamics of aircraft at this size are too fast for most people to control. Fast dynamics can be tamed with control loops, but this requires a very small, very fast servo motor, much smaller than was then available on the market. Payload was another challenge. In the original Lincoln Laboratory study, the technological potential for payloads was in the range of a few grams; DARPA chose not to invest in payloads in its program. Thus, these early vehicles were limited to daylight imaging cameras. System integration was difficult because there was no room for components, such as electrical connectors, in an aircraft with a mass budget of only a few grams of avionics.

The Army and Marines were supportive of the MAV concept, although they wanted aircraft with longer endurances and ranges, day/night imaging, and the ability to fly and perch in urban environments—capabilities that first-generation MAVs could not provide. Also, although these vehicles may be disposable in wartime, they are still too expensive to lose in peacetime training. The principal conclusion in 2000 was that a 6-inch aircraft was too small for a vehicle with the desired performance characteristics. Thus, the near-term focus was shifted to the 8- to 16-inch size range, which has improved the aerodynamics and is better suited to existing payload and subsystem technologies.

What about in the longer term? One way to address the question is to look at the engineering disciplines underlying much of aviation—aerodynamics, propulsion, and structures. Figure 4 shows the trend in the size of air vehicles with payloads that are a constant fraction of the initial mass. The calculations for this figure are for

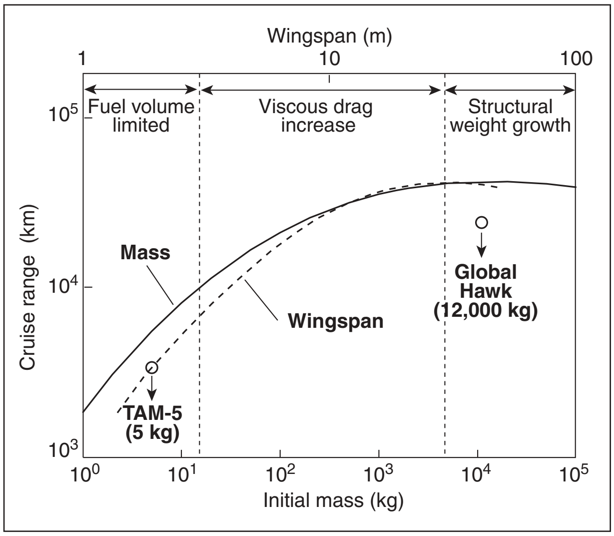

FIGURE 4 Theoretical range of aircraft as a function of size.

subsonic aircraft optimally designed for maximum range at each size (Drela et al., 2003). The figure also shows the performance of the Global Hawk and TAM-5, which have many design requirements in addition to long range, especially low cost. The structure becomes more efficient as aircraft size decreases, but the aerodynamics and propulsion become less efficient. The cubed-square law results in the volume decreasing relative to the area as size is reduced. Thus, smaller aircraft (less than a few thousand kilograms) have somewhat inferior aerodynamics and propulsion and relatively less fuel volume, and therefore less range. Nevertheless, aircraft that weigh less than a kilogram can have very useful, even transoceanic range. This should come as no surprise because birds as small as a 6-gram hummingbird migrate more than 2,000 kilometers without refueling.

As airplanes are scaled down, the aerodynamic and engine performance, the volume/wetted area, and the communications range all decrease while the necessary control bandwidth increases. However, some aircraft parameters do not vary with size. Flight speed, for example, is a function of installed power, not size; flight altitude is a function of flight speed. Recent transatlantic model airplanes had cruise speeds and altitudes comparable to those of the 1919 NC-4 because the performance of current model airplane engines is only marginally better than the performance of the large engines of 80 years ago.

Takeoff and landing speed and, therefore, runway length scale with cruise speed and installed power, rather than aircraft size. This implies that 6-inch transonic aircraft would require runways comparable in length to those of large aircraft (1 to 2 miles). Of course, the runways don't have to be very wide. A more practical solution may be based on favorable structural scaling with decreasing size, which implies that variable geometry is much less costly for very small aircraft than for very large ones. Birds make good use of variable geometry when landing and taking off.

A major reason for the relatively low performance of current MAVs is the poor performance of subsystems, especially the propulsion subsystem. Historically, small airplanes have had small budgets to solve large engineering challenges, and progress is paced by the level of investment. The recent development of semiconductor-based micromachined devices, known as microelectromechanical systems (MEMS), has opened the way to new approaches to small engines. A micromachine gas turbine engine, for example, is sized to power an MAV in the 50-to 100-gram class (Figure 5) (Epstein, 2003). The performance of early versions will be no better than the performances of early turbojets in the 1940s, but greatly superior to the performance of battery-powered vehicles. These engines should increase flight speed and extend the range of MAVs. Other approaches, such as high-performance, miniature, internal combustion engines and fuel cells, are also being pursued. MEMS, improved microelectronics, and associated technologies can greatly improve air vehicles, down to the scale of a few inches.

Can aircraft be smaller still? Most flying insects are an order of magnitude smaller than MAVs, but there is comparatively little quantitative analysis or engineering experience at these length scales. Developments in biotechnology and nanotechnology may help, but, at the moment, neither the utility nor the challenges of subcentimeter-span aircraft are well understood. One thing is clear though, smaller is more difficult.

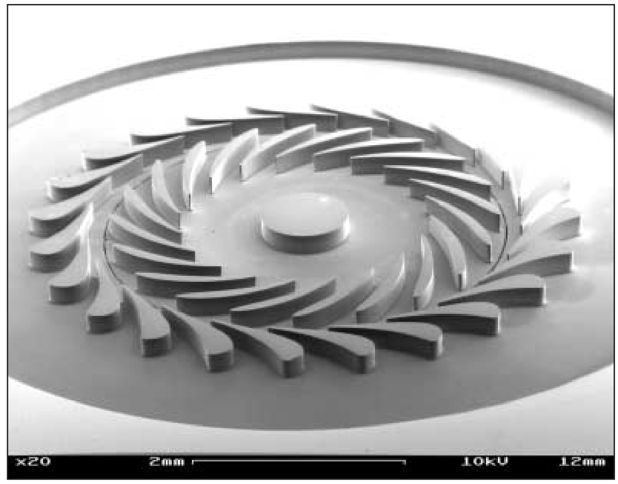

FIGURE 5 A 4-mm diameter, 60-watt MEMS turbine that spins at 1.2 million rpm.

The Future

Forecasting the future of aeronautics can be risky. History is littered with inaccurate predictions of the future of flight. Lord Kelvin once opined that "aircraft flight is impossible." Millikan, von Kármán, Kettering, and others stated in a 1941 National Academy report that "the gas turbine can hardly be considered a feasible application to airplanes." Unbeknownst to them, the first jet plane had flown in Germany the previous year. Nevertheless, it seems fitting that I close with some remarks about what lies ahead.

First, autonomous air vehicles of all sizes will predominate, especially in military aviation, the inevitable result of the continued development of microelectronics and software. Second, the performance of UAVs will improve rapidly both because of increased investment and because small systems can be developed much more quickly than large military aircraft, which now take decades to reach the field. Indeed, progress can be faster for small aircraft for much the same reason that geneticists study fruit flies rather than elephants. Third, improving technology will enable the development of very capable air vehicles as small as a few inches in size. Large aircraft will always have their place, but the future of aeronautics will be small.

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The judicious application of advanced technologies and design innovations gave the F-16 unprecedented performance capabilities at an affordable cost.

Technology and the F-16 Fighting Falcon Jet Fighter

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Harry J. Hillaker

The Lockheed F-16 Fighting Falcon was initially ridiculed and rejected by both the company and the Air Force for being too small and too light to *go anywhere or carry anything* significant. Nevertheless, the F-16 has proven to be an extraordinary fighter. The F-16 has been ordered by 24 countries and is operating in the air forces of more than 20 countries. The judicious application of advanced technologies combined with design innovations gives the airplane its unprecedented combat performance at an affordable cost.

A successful fighter must be orchestrated, not played with a single instrument like a violin or a clarinet, but, rather like an organ, with a vast capacity of sounds, from the highest to the deepest notes and from soft, sweet tones to loud, crashing crescendos. The design of the F-16 was orchestrated in such a fashion. The airplane can also be considered a unity of contradictions: "small" but with long range; "light" but of high strength; "low drag" but with high controllability; and high "g" but pilot tolerant. In the past, interactions between the pilot and the aircraft tended to require that specific, conscious choices be made between various disciplines, but on the F-16 the interactions are largely mutual—one discipline enhances another. Each discipline, or element, is part of an interwoven pattern, with dynamic relationships between the elements.

That the F-16 turned out to be a huge success is not accidental. We dissected the problem, studied it until we understood its interworkings, and adopted a rigorously rational approach. We were very careful not to let even a hint of emotion or bias influence our actions, fully recognizing that a decision based on either would not necessarily be rational. We accepted only facts—facts based on experimental data.

We did not use technology "for technology's sake." We did not consider a technology or a feature unless it reduced weight or increased operational capability with no overall weight penalty. If we added something involving an incremental weight increase, it had to lower the overall weight.

To realize our size objective, we sized the airplane at the start of combat, the condition at which it was to perform its primary mission, instead of at its takeoff gross weight, the point at which its wing loading and thrust loading are defined. The wing loading (wing area), thrust loading, and structural criteria were defined at this point rather than at the takeoff point.

We knew that, with rare exceptions, external fuel tanks are added to fighters after the airplane is defined. Therefore, we decided to include external fuel tanks as part of our configuration definition. The external tanks would be used for takeoff, ascent, and outboard cruising to the start of combat. Under battle conditions, they would be jettisoned, and combat would start with full internal fuel tanks.

By sizing the airplane at the start of combat with full internal fuel tanks—combat, return cruise, and reserve fuel—and using external fuel tanks for the outbound leg of the mission, the empty weight was reduced by 1,470 pounds, and gross weight was reduced by 3,300 pounds. The weight and drag saving produced a generous 30-percent improvement in acceleration time and increased the sustained turn rate by 5 percent. At $289.70 per pound of weight empty this represented about a 10 percent saving in unit flyaway cost.

Achieving our stated design weight objective of less than 20,000 pounds was indeed a challenge, but we were careful not to skimp on anything related to the operational mission objectives. It would have been easy to skimp on structural strength and fuel load—the principal elements that could be varied—but we chose not to. We decided the configuration, or form, would have enough structural strength to match the plane's maneuvering capacity and enough fuel to sustain its combat capability at effective, in fact higher than normal, structural criteria.

The F-16 may be light and small, but it can "bench press" with the best. It is not generally appreciated that the aircraft's "light weight" was not achieved by resorting to high strength-to-weight materials, like titanium or composites, or other exotic materials. Nor was structural integrity sacrificed for the sake of lighter weight. The structural criteria were fully compatible with the aerodynamic capacity of the airplane and the pilot's physical tolerance. The structural design load factor was set at 9.0 g's at start of combat with full internal fuel, as contrasted to the normal military specification of 7.33 g's with only 60 percent internal fuel.

Our approach to the structural design ensured that we could demonstrate the maneuvering capability of the airplane. Air Force ground rules dictate (appropriately) that an airplane be limited to 80 percent of its design takeoff weight until a structural static test has been completed. Because a structural test was not possible within our $37 million contract, we decided to design the two prototypes to 125 percent (a 25-percent margin) of the design loads (80 percent of 125 percent is 100 percent). The weight penalty was small (418 pounds or 3.5 percent). This was an unappreciated decision that contributed indirectly to the success of the prototype program; it was the means by which we were able to demonstrate the sensational, eye-opening maneuverability of the airplane that would otherwise have been restricted by the 80 percent load limit (Figure 1).

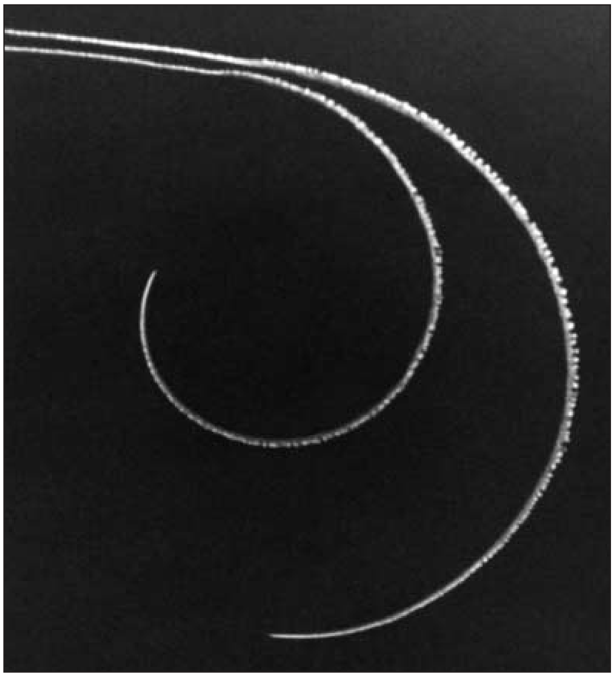

FIGURE 1 Contrails for the F-16 (inner curve) and F-4 Phantom (the aircraft it replaced), showing the superior turning performance of the F-16. Reprinted courtesy of Lockheed Martin.

We also recognized that U.S. military aircraft have a history of remaining in the active inventory for a very long time. Therefore, we doubled the design service life from 4,000 hours to 8,000 hours. To my knowledge, no other fighter has ever been designed to such stringent requirements.

The most visible of the selected technologies and design innovations was the blended wing-body configuration that maximizes the total vehicle lift with a minimum increase in drag. The wing-body blending and forebody strakes are significant beneficial features of the airplane that represent radical departures from other airplane configurations and give the aircraft its unique look. The F-16 has a smooth fairing, or blending, of the body (fuselage) into the wing, rather than the usual sharp intersection; the fuselage blends into the wing cross-sectionally and longitudinally, or lengthwise. Although more of the wing is covered up, the lift lost in that area is more than regained from body lift at high angles of attack when the lift generated by the wing begins to diminish because of flow separation. The forebody strakes generate a strong vortex flow that improves directional stability, delays flow separation over the wing (thus extending life), and gives a more favorable center of lift (Figure 2).

FIGURE 2 Vortices showing the turbulent air flow above the wing created by the strakes. This turbulence provides extra lift. Reprinted with permission from Andy Wolfe.

One of the distinguishing features of the F-16 is the configuration of the engine air inlet, a considerable departure from more conventional configurations. We concluded early on that it would take radical departures from the norm to achieve our lightweight fabrication goals. Thus, the engine air induction system (inlet and air duct) was given major consideration in the definition and integration of the overall airplane configuration (Figure 3).

FIGURE 3 Front view of the engine air inlet. Reprinted courtesy of Lockheed Martin.

A nose inlet similar to the F-86 Sabre, the F-100 Super Sabre, and Vought's F-8 Crusader or A-7 Corsair II, in which the air is undisturbed, would seem to be a logical choice for high angle-of-attack maneuvering. However, there were some drawbacks; the air duct from the inlet to the face of the engine is quite long, extending roughly one-half the length of the fuselage. Long ducts can be beneficial in straightening, or diffusing, flow or pressure distortions that result from high angle-of-attack flight. However, there are also penalties. The high internal duct pressure that occurs during supersonic flight adds considerable weight, and excessive duct length means more friction losses that result in lower pressure recovery. In addition, unless the air duct goes around the cockpit, as it does in the F-100 Super Sabre, instead of under the cockpit, as it does on the Vought F-8 Crusader and A-7 Corsair II, the added side area would have a destabilizing effect on directional stability and would require a bigger vertical tail, which would increase drag and weight (400 pounds). With our emphasis on low weight and maximum thrust, that nose inlet configuration was not acceptable. Besides, the requirement that advanced search-track radars be mounted in the nose precluded the use of such an inlet.

We concluded that we needed an innovative approach to locating the inlet that would be better suited to the desired maneuvering characteristics of the airplane. We finally settled on a position on the lower surface of the forward fuselage, set back some distance from the nose of the airplane—far enough forward to allow a gradual bend in the air duct up to the engine face to minimize flow losses and far enough aft so it wouldn't weigh too much or be too draggy or destabilizing.

We incorporated automatic leading-edge flaps on the wing that increase lift by as much as 18 percent and reduce drag by as much as 22 percent when performing a sustained turn at M = 0.9 at 30,000 feet and reduce the drag at maximum lift by nearly 70 percent. During an instantaneous turn, the energy loss is only a fraction of the loss you get with a fixed camber wing.

One of the revolutionary features of the F-16 is its flight control system, a notable product of advanced technology. The heart of the airplane that gives it life—the brain that determines how it performs and the muscle to make it work—the flight control system is the link that integrates the pilot and the airframe into a highly responsive and effective combat fighter. This advanced system is a radical departure from previous systems. "Fly-by-wire" is a totally electronic system that uses computer-generated electrical impulses, or signals, to transmit the pilot's commands to the flight control surfaces instead of a combination of the push rods, bell cranks, linkages, and cables used with more conventional hydromechanical systems. Without question "fly-by-wire" was the star technology of the F-16. It's the only way to go! Any modern airplane, whether military or commercial, that doesn't incorporate fly-by-wire is archaic, and any company that fails to see its benefits must have its head in the sand.

"Fly-by-wire" is not really an adequate descriptor. After all, early airplanes were flown by stranded wire cables through a series of pulleys that ran from the control stick directly to the control surfaces. The control surfaces did only what the pilot could force them to do, and the pilot got direct feedback from the control surfaces' actions. The pilot literally controlled the airplane; he provided the sensing, the signals, and the power—the muscle. With a fly-by-wire system, the pilot commands roll, pitch, or yaw rate—not surface deflection, as in a conventional system. When the pilot makes a roll input, for instance, he commands a roll rate that varies with the force of his input. If he releases his input, the airplane maintains the resultant bank angle until he makes another control input; he doesn't have to center the "control stick" to maintain the bank angle as he does with a conventional system.

Beyond the necessary control of flight, the pilot has precise response control. The reduced lags and overshoots afforded by the better kinematics of the electronic circuitry results in greatly improved and expanded flying qualities, which, in turn, significantly improve the response and tracking accuracy of the pilot-airframe system. A much higher level of precise, nonvarying control response is possible throughout the flight envelope with the fly-by-wire system than with conventional flight control systems.

The resulting system is a quad-redundant (fail-operative, fail-operative, fail-safe), high-authority, command-and-stability augmentation system. The system consists of a series of sensors (accelerometers, rate gyros, air data converter), computers, selectors, transducers, and inverters that collectively generate the pitch, roll, and yaw rates that are transmitted as electronic signals to the five triplex electrohydraulic, servo-actuators that control the flaperons (roll and flaps), elevons (pitch and roll), and rudder.

The weight saving resulting from the absence of cables, linkages, bell cranks, and the ratio changer was translated into redundancy. The redundancy level and the freedom of routing afforded by wire harnesses improved the reliability and increased the operational survivability of the airplane and contributed to its compactness and small size. With a conventional flight control system, we would have had to route the cables externally, as on the old Ford Tri-motor, to maintain the size or else make the airplane bigger.

The "smarts" should be vested in the pilot, not in the airplane.

Because of the fly-by-wire, all-electronic, computer-based flight control system, some have called the F-16 the "electric jet" or "an airplane wrapped around a computer." I don't feel comfortable with that; I want the "smarts" to remain in the cockpit, to be vested in the pilot. The pilot uses his natural, inherent intellect to govern the airplane; he (or she) makes the airplane "obedient." It responds with minimum commands to the pilot's needs.

In conjunction with the fly-by-wire flight control system, we changed the dynamics of the airplane, which dramatically enhanced its capabilities. We adopted what we called *relaxed static stability*, which meant that, with the center of lift forward of the center of gravity instead of aft of it, the airplane would be statically unstable. No matter, though. With artificial stability, the airplane would be much more dynamic—as much as two and one-half times as dynamic as the F-4C Phantom. Relaxed static stability allowed the airplane to achieve an initial pitch rate of 5 g's per second with "deadbeat" damping—no overshoot. Maneuvers could be instantaneously initiated and precisely controlled—a very important factor.

Another key feature that greatly enhanced the airplane's combat effectiveness was the cockpit, the pilot's office. I know of no other fighter as attentive to the pilot's needs. The canopy, which is one piece—no separate windshield—provides unsurpassed visibility. Some pilots say it makes them feel as though they are riding on the airplane rather than in it. The seat is tilted back 30 degrees, instead of the normal 17 degrees, which increases the pilot's tolerance to high g maneuvers. The control stick is located on the pilot's righthand-side console and has no movement—the force exerted on the stick, or controller, provides signal inputs to the control surfaces.

Speaking metaphorically, the F-16 initially had a torturous mountain to climb, a vast turbulent ocean to cross, a vicious dragon to slay on its way to reality, and it has proved to be one of the premier fighters in the world. Nothing can detract from that. The F-16 shows that the application of advanced, and unproven, technologies need not result in an expensive aircraft. When applied properly, it can do just the opposite. It should be noted that 30 years after its first flight the F-16 is still being procured.

In the twenty-first century, we will see the dawn of the space fleet.

The Evolution of Military Aviation

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Michael A. Clarke

In the 100th year of powered manned flight, it is appropriate that we step back and review the evolution of military aviation and look ahead to the future. How did the United States achieve its current dominance in the air? I believe many factors have played a role—innovations by aerospace engineers from many nations, the visionary ideas of a few individuals, and the means (and willingness) to spend significant portions of our wealth on military equipment. America was founded by people seeking to distance themselves from relatively static societies, people attracted to building a new land and developing a new society. The spirit of these individuals, as embodied in America's engineers, is largely responsible for our success as a nation and particularly for our success as aviation innovators.

Throughout the nineteenth century and the continuing Industrial Revolution, great strides were made in engineering, medicine, physics, chemistry, and other scientific fields. Man's horizons were expanded again and again, but one of the greatest challenges of all—the ability to fly—remained a challenge. In the twentieth century, no greater progress was achieved than in aviation (with the possible exception of the rise of electronic systems).

Think of it. A little more than 10 years after the first powered flight by the Wright brothers in 1903, there was dogfighting over Europe; 20 years later, commercial aviation began; 30 years later, there were routine passenger flights; 40 years later, jet aircraft; 44 years later, level, supersonic flight; 50 years later, the possibility of atomic powered aircraft; 60 years later, Mach 3 planes; and 70 years later, the Concorde.

Behind these achievements stand pioneers of military aviation, such as Orville and Wilbur Wright, Giulio Douhet, Billy Mitchell, Manfred Von Richtoffen, Willy Messerschmidt, Ernst Heinkel, Artem Mikoyen and Mikhail Guerevitch (MiG), Eddie Rickenbacker, James Doolittle, Glenn Curtiss, William Boeing, Leroy Grumman, Igor Sikorsky, Kelly Johnson, Chuck Yeager, Scott Crossfield, Pete Knight, Harry Hillaker, and a multitude of others whose names we do not know. These aviators and engineers of the past have provided the basis for where aviation is today and where it can go in the future. Each nation can determine its own aviation destiny. In the case of the United States, we have reached a fundamental decision point on the vector for future military aviation, and moving forward will require all of the engineering skills we have developed over the past century.

The War Years

By World War I, aviation enthusiasts here and abroad had become convinced that the refinement of airplanes would lead to greatly advanced military capabilities. At first, airplanes merely provided a vertical battlefield perspective, replacing the balloons that had been used for this purpose since the American Civil War. When the enemy began to counter this advantage, aircraft were armed, air battles ensued, and dogfighting tactics were developed. The regular Army was not impressed, however, maintaining that aviation was peripheral to the serious business of ground warfare.

In the 1920s, General Billy Mitchell demonstrated the vulnerability of the naval fleet to attack from the air and was rewarded with a court martial and an ignominious end to his career. In the 1930s, America and the rest of the world slumbered while Goering, with Hitler's support and approval, built the German air fleet.

World War II was the supreme wakeup call. At the outset of the war, U.S. Army and Navy aircraft were inferior in almost every way to German and Japanese aircraft. But thanks to innovative engineers, by the later stages of the war, our aircraft were significantly superior to those of our adversaries. We also learned to use our admittedly inferior machines to advantage. Billy Mitchell was vindicated by the battle of Midway, which changed the course of the war in the Pacific, when Japan's offensive naval superiority, embodied by aircraft carriers, was destroyed by American naval dive bombers, all technically inferior to the Japanese Zero. British and American bomber fleets also had a significant effect on the progress of the war in Europe. These lumbering aircraft developed new covering formations to protect against Luftwaffe fighters; to fall out of formation was to be fatally exposed.

The concept of close air support of land forces, developed by the Germans and the Russians, greatly increased the capabilities of land forces. Adopted and perfected after the war by many nations, close air support became a mainstay of U.S. fighters by the end of WWII and was used even more successfully in Korea and Vietnam.

In the early 1930s, the jet engine was invented. Credit is usually given to Sir Frank Whittle of Great Britain (first to apply for a patent) and Dr. Hans von Ohain of Germany, whose engine was installed on a Heinkel He-178 and was the first to fly in 1939. During the war, Germany, England, and America continued working on jet engines and the aircraft they would power. Hitler planned to develop a jet-powered bomber but finally had to settle for a fighter—the Messerschmitt Me-262 (Figure 1), which was generally untouchable by allied propeller aircraft because of its speed. However, the Me-262 had a limited range because of excessive fuel consumption and limited targeting capability at high speed. Fortunately, the war ended before it could be perfected.

FIGURE 1 The Messerschmitt Me-262, the German jet-powered fighter, was flown during WWII. Photo courtesy of *www.fighter-planes.com*.

At the same time, the atomic bomb was under development, and it is now well documented that the Germans had almost succeeded in developing one when the war ended. On August 6, 1945, the Enola Gay dropped the first atomic bomb on Hiroshima, deliverable only by an aircraft like the B-29 that could carry heavy munitions. Bockscar, another B-29, struck Nagasaki three days later, arguably hastening the surrender of Japan.

The 1950s and 1960s and the Cold War

In the wake of World War II, the future of aviation in America looked extremely bright. No idea or concept seemed too farfetched to consider, and anything seemed possible. The Korean War signaled the end of the propeller-powered fighter and ushered in the era of the jet fighter. The jet fighter tactics used today were developed during dogfights between North American F-86s and MiG 15s over Korea.

The Century series of aircraft for the Air Force, consisting of supersonic fighters (the F-100, F-101, F-102, the F-104, Starfighter [Mach 2 plus], the F-105 and the F-106), new bombers (the B-47 and the B-52, which is still in the inventory), jet airliners, and the XB-70 (Figure 2) (designed to sustain Mach 3 and, for its size, probably the most remarkable aircraft of all) were all in development. The X-15 had extended manned flight all the way to Mach 5. The F-12, which led to the Mach 3 SR-71 high-speed reconnaissance aircraft, was flying. Sixty-five years after Wilbur and Orville's remarkable first powered flight, the golden age of military aviation had arrived.

FIGURE 2 The XB-70 was designed to sustain Mach 3. Photo courtesy of *www.fighter-planes.com.*

America's air fleet was developed with the Cold War in mind. The need for long-range bombers that could carry nuclear weapons led first to the B-47 and then to the B-52. Fighters were designed for both conventional and nuclear wars; aircraft as early as the F-84 and the F-100 were modified to carry nuclear weapons. Almost all subsequent fighter aircraft have retained that capability.

The war in Vietnam was a crucible for the development of new systems, the use of aircraft in unaccustomed roles, and the development of tactics for air attack (many of which have since been perfected in the conflicts in Kosovo, Afghanistan, and Iraq). In Vietnam, the B-52 was modified to carry enormous quantities of conventional bombs, which may well keep the B-52 in the inventory until approximately 2040 in this capacity; for more heavily defended targets, the B-52 can be a missile platform for launching high-speed, long-range cruise missiles. When existing aircraft were unable to destroy a bridge span easily, engineers and visionaries returned to the drawing board to develop precision-guided munitions. They also invented missile systems to strike radars that guided enemy ground-to-air missiles, improved the sensitivity, sorting, and tracking capabilities of aircraft radar, and created heads-up displays and many other innovative features.

Efforts to supplement conventional aircraft with vertical-takeoff systems were also under way. The British developed the Kestrel, which became the Harrier aircraft used by the U.S. Marine Corps. Vertical-takeoff aircraft are not restricted to airfields and can be dispersed to tactical advantage. The latest technology is in the propeller-powered V-22 and the vertical/short takeoff and landing (V/STOL) version of the F-35 Joint Strike Fighter now in development.

Today's Fighters

With the lessons of Vietnam still fresh in the minds of developers and the need to cope with Soviet aircraft in a larger war still pressing, a new generation of military aircraft was beginning to emerge. It was clear to military planners that an air war with the Soviet Union would be difficult for American and allied air forces to win. Intelligence indicated that not only was a new generation of Soviet aircraft under development, but also that the numbers of Soviet aircraft were staggering. To prevail in the European battle scenario, the United States and its allies would have to destroy at least four Soviet aircraft for every one of ours. This "exchange ratio" of four to one meant that our aircraft and systems had to be superior, in fact, vastly superior. This necessity gave rise to the next major evolution of military jet aircraft—the F-15 (Figure 3). Designed primarily for air-to-air combat, the F-15 was a remarkable engineering feat.

In the meantime, the Russians were far from idle. Based on experience with the MiG 15 and MiG 17, the Soviets developed aircraft comparable to the best aircraft in the U.S fleet. The Sukhoi Su-27 (Figure 4) was designed specifically to offset the F-15; the MiG 29 is in the same category. Both aircraft have unusual

FIGURE 3 The F-15 is designed primarily for air-to-air combat. Photo courtesy of *www.fighter-planes.com.*

FIGURE 4 The Sukhoi SU-27 was designed to affect the F-15. Photo courtesy of *www.fighter-planes.com.*

handling characteristics at high angles of attack that our systems cannot emulate.

Shortly after the debut of the F-15, there was a campaign to produce a less costly, lightweight fighter. Two lightweight prototypes were procured, the General Dynamic (now Lockheed Martin) F-16 and the Northrop F-17; a fly-off competition was won by the F-16 (Figure 5). The F-16 was the first "fly-by-wire" production aircraft. The fly-by-wire capacity eliminated the need for backup mechanical control systems, which had added considerable weight to the aircraft. The lighter weight also contributed to the F-16's extraordinary maneuverability. These aircraft represent the culmination of the fighter jet; in fact, additional maneuvering capabilities would only exceed the pilot's physical ability to withstand the forces generated. Thus, the F-16 is limited by its onboard computer to "g" loads pilots can accommodate (usually 9 g's).

FIGURE 5 The F-16 is lighter weight and more maneuverable than the F-15. Photo courtesy of Lockheed Martin.

Later, a naval version of the F-17 (now in the hands of McDonnell Douglas) was purchased by the Navy and designated the F-18. McDonnell later merged with Boeing, which is now the prime contractor for the F-18 and its variants, as well as the F-15. These three aircraft, the F-15, the F-16, and the F-18, with their variants, still comprise the heart of the U.S. fighter fleet. They will not be surpassed until the F/A-22 enters the inventory (around 2005). The F-16 is now also flown by Belgium, the Netherlands, Norway, Denmark, and a host of other nations. Japan has built its own version of both the F-15 and the F-16; Israel also operates both. Australia and Canada have opted for the F-18.

At the same time, new aircraft were appearing. In the late 1970s, stealth aircraft were invented. Based on the musings of Russian scientists, "stealth" methods reduce radar cross section so that stealth aircraft are nearly invisible to enemy radars. The technology involves the application of materials that absorb radar energy and aircraft shape management (e.g., the F-117 [Figure 6] and the B-2). Stealth techniques have increased the probability of survival of attacks into hostile airspace.

FIGURE 6 The F-117 has "stealth" characteristics to survive attacks into hostile airspace. Photo courtesy of *www.fighter-planes.com.*

Around 1980, the concept of the advanced tactical fighter, now known as the F/A-22, emerged (Figure 7). Designed to meet the demands of the Cold War, this remarkable aircraft was developed to fly safely on the "red" side of the battle area; it not only has stealth capabilities, but also has the ability to supercruise (i.e., to fly at supersonic speeds without the use of an afterburner), thereby reducing fuel flow, extending range, and limiting the time of exposure to enemy antiaircraft systems.

Figure 7 The F/A-22 will be the most capable fighter ever built. Photo courtesy of *www.fighter-planes.com.*

To understand the "birthing" difficulties of the F/A-22, one has to understand some of the basics of modern aircraft procurement. All military aircraft must be justified within the authority of the President's budget, and the services develop prospective budgets for each new system based on several planning factors: the total number of aircraft needed to meet force requirements; nonrecurring development costs; unit cost estimates based on assumptions about production rate; predictions by vendors of production learning curve effects; and other factors.

Initially, the F/A-22 was expected to be operational by the early 1990s; that date has been extended to at least 2005. The total number of aircraft and the anticipated production rate have both been reduced to well below the initial pricing parameters. When you add the costs associated with the F/A-22's incredibly complex avionics systems, which has been reinvented over and over again, you begin to understand the extreme increase in cost of the aircraft. Nevertheless, the F/A-22 will almost certainly be the most capable fighter aircraft ever built.

Thoughts for the Future

Since WWII, no one has even tried to challenge American airpower or that of our European allies. The Russians are mired in the aftereffects of the Cold War and a collapsed economy. Once-prominent aircraft manufacturers have been reduced to selling their inventories of fighter aircraft to foreign buyers, but there are few takers, and new systems are beyond their financial reach. The Japanese have been content to operate modified American systems. The Chinese, whom some believe will be the greatest threat in the future, do not seem intent on demonstrating advanced aircraft systems. The Europeans are cooperatively building fighter aircraft systems with capabilities that will rival, but not exceed, the capabilities of the F-15 and F-16, not to mention the F/A-22. The newest fighter, the F-35 Joint Strike Fighter, is only marginally superior to the F-16, although it does have significant flexibilities, efficiencies, and some new capabilities, and it is being produced with advanced manufacturing techniques.

It is said that no American serviceman has been killed in battle by enemy air attack in the past 50 years. The Army now designs new systems based on the assumption that protection from above will almost always be provided by friendly air forces. Will our military aircraft fleet ever be challenged? If not, how do potential adversaries approach conflict with the United States? There are several possible scenarios.

The first scenario requires little analysis. In this scenario, there will be no technologically adept opponent of nearly equal capabilities for the foreseeable future. The grossly asymmetrical forces arrayed against us will not require improvement to our air forces. These dispersed, clandestine, and supranational enemies present few targets from the air, and the usefulness of airpower against these adversaries will continue to be marginal. Thus, our current force seems more than adequate.

In the second scenario, we assume that a technologically adept military competitor appears. In this case, we should be forewarned by intelligence agencies so that we can take the necessary steps to improve our systems. The current force, as modified, with the addition of the F/A-22 and the F-35 should be sufficient for at least the next 20 years. This scenario currently prevails among military planners.

A more worrisome scenario would be the nullification of U.S. military airpower by an unexpected technological advancement or breakthrough that cannot be countered quickly. Examples might include systems that negate stealth advantages coupled with weapons we cannot counteract or space-based systems that are out of our reach that could destroy our assets quickly. One can only hope that engineers somewhere are working on countering these eventualities.

With the advent of new unmanned aircraft systems, the risk to human beings may be greatly reduced. These systems are still in their infancy, probably comparable to aircraft in the 1950s, but the possibilities for their future application are endless, and new tactics are being developed every day. But I do not believe the age of the fighter pilot is over, although the future will be very different. Unmanned machines under the control of fighter pilots flying in proximity may well represent the air power of the future—unmanned machines that can accomplish feats beyond the physical abilities of any man or woman, without the human risk.

Unmanned systems are still in their infancy, probably comparable to aircraft in the 1950s.

Finally, we must consider space as a future battlefield, as well as systems that will allow its exploitation and will have some synergistic effects on the capabilities of air-breathing systems. In the 1960s, partial-orbit or fully orbital military systems were under consideration but were not implemented. Although the use of space for military power could be dreamed of, the underlying enabling knowledge and technologies did not yet exist. Everyone acknowledged that the first country to "own" space would "own" the planet, but the military did not have the technologies, budget, or the inclination to lead the nation to space. Even the National Aeronautics and Space Administration (NASA), after visiting the moon, was content to fly the shuttle in low Earth orbit and develop unmanned systems to explore other planets. This attitude persists to the present day.

In the late 1970s, the concept of an "aerospace plane" for space access emerged, but after the expenditure of more than a billion dollars, the project was shelved as technologically unachievable. The dream of flying to orbit in a hybrid, air-breathing/rocket system had to be abandoned. Later attempts were equally unsuccessful.

In various laboratories, experimentation is under way to develop ramjet and scramjet engines as the only way to achieve and sustain air-breathing flight above Mach 3 in the atmosphere. But after 50 years of effort, no production systems have emerged. In fact, it has only recently been verified that scramjet engines can actually fly and produce positive thrust; and this was accomplished in Australia.

In short, despite our ingenuity and engineering skill, we have not realized the benefits of greatly increased speed for commercial and military aircraft systems. Once Boeing dropped out of the supersonic airliner business, the Concorde was the only supersonic (Mach 2) commercial production aircraft to be operated successfully (but not economically).

In 1963, President Kennedy challenged Americans to land a man on the moon by the end of that decade and return him safely to Earth. Although in hindsight, this challenge seems foolhardy, it was met in 1969. Many now argue that the effort wore us out without delivering anything useful. I strongly disagree. Although many aspects of the project were premature, no one can dispute that the Herculean effort exemplified the best that our engineering talent could deliver. Grand plans need grand strategies, strategies that include a road map for what comes after the immediate challenge has been met. And there was no post-Apollo plan supported by the American public. This was not the fault of the engineering community but a failure of national leadership.

Three decades after Apollo, we still have no comparable vision for man in space. A plethora of unmanned systems have contributed collectively to our current standard of living and our nation's military capabilities. Communications satellites provide nearly instantaneous television pictures from halfway around the planet. Weather satellites warn of impending disasters. Reconnaissance satellites keep the military informed of the activities of potential adversaries. Low, medium, and geosynchronous stationary orbits are filled with vehicles and systems, and new microsatellite arrays will soon be launched. The success of the global positioning system (GPS) satellite array has been phenomenal. But, with the exception of the space shuttle and temporarily manned orbiting systems, our space capability does not involve the presence of human beings and does little to satisfy our thirst for exploration. One can hope that the recently enunciated space vision of President Bush will lead to the development of a strategy for the moon and beyond that can be fully supported by the American people.

The challenges in materials science, thermal management, and many other technical areas to operate within the atmosphere at speeds above Mach 5 are too great, I believe, for an economical manned system (missile systems may be possible). Hybrid horizontal takeoff and landing systems, using both rocket and air-breathing propulsion for access to space, seem more likely. These systems could be useful for both military and commercial purposes and could avoid some of the extreme challenges of very high speed operations within the atmosphere. Military aircraft of the future will almost certainly operate in both air and space.

In the twenty-first century, we will see the dawn of the space fleet. The U.S. Department of Defense (DOD) is currently championing the National Aerospace Initiative (NAI), a communications and coordination device to bring together NASA, DOD, and service executives to discuss the development of hypersonic and space-access systems and space technologies. NAI offers the prospect of eliminating redundancies, encouraging cooperative ventures, and taking advantage of opportunities for economies and efficiencies that might otherwise be missed. A multilevel organization for cooperation has been established to accomplish NAI goals. If NAI is endorsed by the President, it could ensure U.S. advancement to space. Great challenges lie ahead, but I believe we can overcome them—as we carry on in the spirit of innovation that characterized the evolution of military and commercial aircraft in the twentieth century.

NAE News and Notes

NAE Newsmakers

Robert Langer, Kenneth J. Germeshausen Professor of Chemical and Biomedical Engineering, Massachusetts Institute of Technology, was awarded the **Heinz Award** at a private ceremony in Pittsburgh, Pennsylvania. In her presentation of the award, Teresa Heinz, chairman of the Heinz Family Foundation, remarked, "Dr. Robert Langer is a medical pioneer in the guise of an engineer. He has created new science, revolutionizing the delivery of drugs and the engineering of human tissue, two new areas of discovery that offer the promise of recovery to those afflicted with a variety of conditions. A peerless and perseverant trailblazer, he has made contributions that touch ours and future generations. Dr. Langer is a truly worthy recipient of the Heinz Award for Technology, the Economy and Employment." Recipients receive $250,000 and a medallion inscribed with the image of Senator Heinz.

The Institute of Electrical and Electronics Engineers (IEEE) has named **Tadahiro Sekimoto**, chairman of the Institute for International Socio-Economic Studies in Tokyo, recipient of the 2004 **IEEE Medal of Honor**. Dr. Sekimoto was honored for "pioneering contributions to digital satellite communications, promotion of information technology R&D, and corporate leadership in computers and communications." A foreign associate of NAE, Dr. Sekimoto has also been awarded the Purple and Blue Ribbon Medals from the Emperor of Japan, Order National de la Legion d'Honneur (Commandeur and Officier), Honorary Knight Commander of the Most Excellent Order of the British Empire, and Commander First Class of the Royal Order of the Polar Star from the King of Sweden.

Burton J. Smith, chief scientist, Cray Inc., was awarded the **Seymour Cray Award** given by the IEEE Computer Society Board of Governors for "innovative contributions to high-performance computing that best exemplify the creative spirit demonstrated by the late Seymour Cray." The award includes a crystal model, a certificate, and an honorarium of $10,000. Dr. Smith accepted the award at SC2003, the annual high-performance computing conference, held this year in Phoenix, Arizona.

Robert H. Wagoner, George R. Smith Chair, Department of Materials Science and Engineering, Ohio State University, received the **2004 Distinguished Service Award** from the Minerals, Metals and Materials Society (TMS) in recognition of his outstanding contributions to TMS. Dr. Wagoner received the award during the 133rd Annual Meeting of TMS in Charlotte, North Carolina.

Jack Wolf, Stephen O. Rice Professor, University of California, San Diego, has been selected by the IEEE to receive the 2004 **Richard W. Hamming Medal**. Dr. Wolf was honored for "fundamental contributions to the theory and practice of information transmission and storage." The award, sponsored by AT&T Labs, which has been given annually since 1986 for exceptional contributions to information sciences, systems and technology, is named in honor of **Richard W. Hamming**, who played a central role in the development of computers and computing science.

Class of 2004 Elected

In February, the National Academy of Engineering (NAE) elected 76 new members and 11 foreign associates, bringing the total U.S. membership to 2,174 and the number of foreign associates to 172. Election to the National Academy of Engineering is among the highest professional distinctions that can be accorded to an engineer. Academy membership honors those who have made "important contributions to engineering theory and practice, including significant contributions to the literature of engineering theory and practice" and those who have demonstrated accomplishment in "pioneering . . . new fields of engineering, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education."

A list of the newly elected members and foreign associates follows, with their primary affiliations at the time of election and a brief statement of their principal engineering accomplishments.

New Members

Jamal J. Azar, Professor Emeritus of Petroleum Engineering, University of Tulsa, Tulsa, Oklahoma. For the development of improved methods of removing drill cuttings from highly deviated oil and gas wells.

Siva S. Banda, senior scientist and leader, Control Science Center of Excellence, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio. For leadership in the development of multivariable control theory and its applications to military vehicles.

George H. Born, professor, Department of Aerospace Engineering Sciences, University of Colorado, Boulder. For contributions to satellite orbit determination and for applications of satellites to geophysics and oceanography.

David E. Borth, corporate vice president and director, Communications Research Laboratories, Motorola Corporation, Schaumburg, Illinois. For contributions to the development of digital wireless communication systems through improved design and technical management.

Rodney A. Brooks, director, Computer Science and Artificial Intelligence Laboratory, and Fujitsu Professor of Computer Science, Massachusetts Institute of Technology, Cambridge. For contributions to the foundations and applications of robotics, including the establishment of consumer and hazardous-environment robotics industries.

Brian J. Cantwell, Edward C. Wells Professor and Chair of Aeronautics and Astronautics, Stanford University, Stanford, California. For studies of the space-time structure of turbulent flows and for the development of fast-burning fuels for hybrid propulsion.

Arup K. Chakraborty, Warren and Katherine Schlinger Distinguished Professor and Chair, Department of Chemical Engineering, University of California, Berkeley. For the application of theoretical chemistry to practical problems, including immune system recognition, polymer interfaces, sensor technology, and catalysis.

Vernon L. Chartier, Power System EMC Consultant, Beaverton, Oregon. For contributions to the understanding and characterization of electromagnetic fields associated with high-voltage AC and DC transmission lines.

Young-Kai Chen, director, High-Speed Electronics Research, Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey. For contributions to the development of high-speed compound semiconductor electronics and optoelectronics for telecommunications.

Sunlin Chou, senior vice president and general manager, Technology and Manufacturing Group, Intel Corporation, Hillsboro, Oregon. For pioneering work on silicon processes resulting in 35 years of improvements in accordance with Moore's law.

Larry A. Coldren, director, Optoelectronic Technology Center, Defense Advanced Research Projects Agency, and Fred Kavli Professor of Optoelectronics and Sensors, University of California, Santa Barbara. For major contributions to diode lasers, especially vertical-cavity and widely tunable distributed Bragg reflector (DBR) lasers.

Stephen C. Cowin, CUNY Distinguished Professor of Mechanical and Biomedical Engineering, City College of the City University of New York, New York City. For contributions to orthopaedic biomechanics, the mechanics of granular materials, and the mechanics of anisotropic elasticity.

Charles R. Cushing, president, C.R. Cushing & Co. Inc., New York City. For pioneering contributions to worldwide containerized shipping.

Paul D. Dapkus, William M. Keck Chair in Engineering, Department of Electrical Engineering and Electrophysics, University of Southern California, Los Angeles. For contributions and leadership in the development of materials and technologies for photonic devices.

Delbert E. Day, Curator's Professor Emeritus of Ceramic Engineering, Department of Civil and Environmental Engineering, and senior investigator, Graduate Center for Materials Research, University of Missouri-Rolla. For the development of radiotherapeutic glass micro-spheres and their transfer to medical applications.

Ricardo Dobry, professor of civil engineering, Rensselaer Polytechnic Institute, Troy, New York. For fundamental contributions to multiple aspects of geotechnical earthquake engineering.

Elizabeth B. Dussan V., scientific adviser, Schlumberger-Doll Research, Ridgefield, Connecticut. For innovative contributions to the wetting of solids and complex flows in porous media.

Michael L. Eskew, chairman and chief executive officer, United Parcel Service of America, Atlanta, Georgia. For contributions to the development of technology to automate and integrate business processes for efficient on-time worldwide shipping of packages.

Eli Fromm, LeRoy A. Brothers Professor, Education Research and Development, Drexel University, Philadelphia. For innovation and leadership in the development of a holistic curriculum for engineering education.

Zvi Galil, dean, Fu Foundation School of Engineering and Applied Science, Columbia University, New York City. For contributions to the design and analysis of algorithms and for leadership in computer science and engineering.

Gerald E. Galloway, vice president, Enterprise Engineering Group, Enterprise Services and Solutions Sector, Titan Corporation, Fairfax, Virginia. For distinguished leadership in the management of sustainable water resources and in education in environmental engineering.

Richard Gambino, professor, Magnetic-Optics Group, Department of Materials Science and Engineering, State University of New York at Stony Brook. For the discovery of magnetic anisotropy, the enabling technology of magneto-optical recording.

Nicholas J. Garber, professor and chairman, Civil Engineering Department, University of Virginia, Charlottesville. For significant contributions to national and international engineering education and research in traffic operations and safety.

Preston A. Henne, senior vice president, Programs, Engineering, and Test, General Dynamics Gulfstream Aerospace Corporation, Savannah, Georgia. For new concepts in aerodynamic design and their application to award-winning aircraft.

Charles O. Holliday Jr., chairman and chief executive officer, E.I. duPont de Nemours & Co., Wilmington, Delaware. For leadership in DuPont's tranformation to sustainable growth through biotechnology, high-performance materials, improved safety, and consumer protection.

Csaba Horvath, Roberto C. Goizueta Professor of Chemical Engineering, Yale University, New Haven, Connecticut. For pioneering the concept and the reduction to practice of high-pressure liquid chromatography (HPLC) and for leadership in the development of bioanalytical techniques.

Van Jacobson, chief scientist, Packet Design LLP, Mountain View, California. For contributions to network protocols, including multicasting and the control of congestion.

Rakesh K. Jain, director, Edwin L. Steele Laboratory, Department of Radiation Oncology, Massachusetts General Hospital, Boston. For the integration of bioengineering and tumor biology and imaging gene expression and functions *in vivo* for drug delivery in tumors.

Biing-Hwang (Fred) Juang, Motorola Foundation Chair Professor and GRA Eminent Scholar, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta. For contributions to speech coding and speech recognition.

Pradman P. Kaul, chairman and chief executive officer, Hughes Network Systems Inc., Germantown, Maryland. For leadership in the development of satellite communication networks.

Jeong H. Kim, professor of practice, electrical, and computer engineering, University of Maryland, College Park. For contributions to national defense and security through improved battlefield communication.

Yoram Koren, Paul G. Goebel Professor of Engineering, University of Michigan, Ann Arbor. For contributions to the science, education, and practice of manufacturing through innovations in reconfigurable manufacturing systems, robotics, and manufacturing system control.

William A. Kuperman, director and professor, Marine Physical

Laboratory, Scripps Institution of Oceanography, University of California, San Diego. For international leadership in the development and application of computational methods for ocean acoustics.

E. Trifon Laskaris, chief technologist, Imaging Technologies, GE Global Research, Niskayuna, New York. For pioneering contributions to the design and construction of superconducting magnets for magnetic resonance imaging systems.

Frank T. Leighton, professor of applied mathematics, Massachusetts Institute of Technology, Cambridge. For contributions to the design of networks and circuits and for technology for Web content delivery.

Kenneth Levy, chairman, Board of Directors, KLA-Tencor Corporation, Milpitas, California. For the development and commercialization of automated inspection systems for the semiconductor industry.

Chain T. Liu, senior corporate fellow and group leader, Oak Ridge National Laboratory, Oak Ridge, Tennessee. For advancing ordered metallic compounds from the laboratory to practice.

Andrew J. Lovinger, director, Polymers Program, Division of Materials Research, National Science Foundation, Arlington, Virginia. For correlating the processing, structure, and properties of important polymeric materials, particularly electronic polymers.

David M. Maddox, consultant, and general (retired), U.S. Army, Arlington, Virginia. For furthering the integration of operations research into U.S. Army planning and operations at all levels.

David A. Markle, chief technical officer, Ultratech Stepper Inc., San Jose, California. For the invention and development of advanced photolithography systems used to manufacture semiconductor devices.

Roger L. McCarthy, chairman of the board, Exponent Inc., Menlo Park, California. For major contributions to improved vehicle safety and for methods of quantitative assessment of the reliability of complex mechanical systems.

Kishor C. Mehta, P.W. Horn Professor of Civil Engineering and director, Wind Engineering Research Center, Texas Tech University, Lubbock. For systematic studies of structural damage caused by windstorms and leadership in the development of structural design standards for wind loads.

Joan L. Mitchell, IBM Fellow, International Business Machines Corporation, Boulder, Colorado. For leadership in setting standards for the formation of photographic fax and image compression.

A. Richard Newton, dean, College of Engineering, University of California, Berkeley. For innovations and leadership in electronic design automation and for leadership in engineering education.

K. Osseo-Asare, professor of metallurgy and geo-environmental engineering, Pennsylvania State University, University Park. For contributions to the fundamental understanding of interfacial phenomena in leaching and solvent extraction.

Raymond E. Ozzie, founder, chairman, and chief executive officer, Groove Networks Inc., Beverly, Massachusetts. For the conception and development of online collaboration products, including Lotus Notes.

Lawrence Page, president for products, Google, Mountain View, California. For the creation of the Google search engine.

Athanassios Z. Panagiotopoulos, professor, Department of Chemical Engineering, Princeton University, Princeton, New Jersey. For the invention of the Gibbs ensemble method of molecular simulation of phase equilibrium and the development of computational techniques for studying complex fluids.

Denny S. Parker, senior vice president, Brown and Caldwell Inc., Walnut Creek, California. For significant advances in the scientific understanding, engineering development, and process design of chemical, physical, and biological processes for the treatment of wastewater.

John H. Perepezko, professor, Department of Materials Science and Engineering Physics, University of Wisconsin-Madison. For innovations in solidification processing to obtain useful microstructured, nanostructured, and amorphous materials.

Linda R. Petzold, director, Computational Science and Engineering Programs, and professor, mechanical and environmental engineering and computational science, University of California, Santa Barbara. For advances in the numerical solution of differential/algebraic equations and their incorporation into widely distributed software.

Julia M. Phillips, director, physical and chemical sciences, Sandia National Laboratories, Albuquerque, New Mexico. For leadership and distinguished research in the epitaxy of dissimilar materials.

Rajagopal S. Raghavan, senior staff associate (retired), Phillips Petroleum Company, Tulsa, Oklahoma. For pioneering contributions to the interpretation of pressure data in wells to improve the definition, engineering, and production of complex oil and gas reservoirs.

Kenneth L. Reifsnider, Pratt and Whitney Chair Professor in Design and Reliability, University of Connecticut, Storrs. For the development of strength-life relationships in composite materials and structures.

Bruce E. Rittmann, John Evans Professor of Civil Engineering, Northwestern University, Evanston, Illinois. For pioneering the development of biofilm fundamentals and contributing to their widespread use in the cleanup of contaminated waters, soils, and ecosystems.

Jonathan M. Rothberg, president and chief executive officer, CuraGen Corporation, Branford, Connecticut. For the application of engineering principles to the mining of genomic information for the discovery and development of new drugs.

Andrew P. Sage, University Professor and First American Bank Professor, George Mason University, Fairfax, Virginia. For contributions to the theory and practice of systems engineering and systems management.

Shivaji Sircar, professor of practice, Chemical Engineering Department, Lehigh University, Bethlehem, Pennsylvania. For contributions to the fundamental science and technology of adsorption separations and their applications in process industries.

Alfred Z. Spector, vice president, services and software, IBM Research Division, IBM Corporation, Hawthorne, New York. For the design, implementation, and commercialization of reliable, scalable architectures for distributed file systems, transaction systems, and other applications.

Gary K. Starkweather, architect, Microsoft Corporation, Redmond, Washington. For the innovative application of optical technologies to computing, including the invention of the laser printer.

Anne L. Stevens, group vice president, Canada, Mexico, and South America, Ford Motor Company, Dearborn, Michigan. For leadership in the development and application of creative manufacturing processes resulting in major improvements in efficiency and product quality and cost savings.

G.W. (Pete) Stewart, professor, Computer Science Department, University of Maryland, College Park. For the development of numerical algorithms and software widely used in engineering computation.

Robert L. Street, William Alden and Martha Campbell Professor, School of Engineering, Stanford University, Stanford, California. For contributions in groundwater transport, computational and turbulence closure schemes for environmental fluid dynamics, and river restoration.

Bjarne Stroustrup, College of Engineering Professor of Computer Science, Texas A&M University, College Station. For the creation of the C++ programming language.

Stanley C. Suboleski, commissioner, Federal Mine Safety and Health Review Commissioner, Washington, D.C. For increasing the productivity and improving the safety of coal mines through innovative engineering, operating, and educational practices.

Ronald D. Sugar, chief executive officer and president, Northrop Grumman Corporation, Los Angeles, California. For major contributions to advanced space communication systems and leadership in innovative aerospace programs.

Esther S. Takeuchi, vice president of research and development, Wilson Greatbatch Technologies Inc., Clarence, New York. For the development of silver/vanadium oxide batteries for implantable cardiac defibrillators and lithium/carbon monofluoride cells to power implantable pacemakers.

George Tchobanoglous, Professor Emeritus, Department of Civil and Environmental Engineering, University of California, Davis. For contributions to engineering education, engineering practice, and public service in the field of environmental engineering.

Richard L. Tomasetti, cochair, Thornton-Tomasetti Group Inc., New York City. For innovative structural engineering in the design of high-rise buildings and long-span structures.

Daniel C. Tsui, Arthur Legrand Doty Professor of Electrical Engineering, Princeton University, Princeton, New Jersey. For contributions to the understanding of quantum physics of two-dimensional electron systems at semiconductor interfaces.

Vijay Vittal, Harpole Professor, Department of Electrical and Computer Engineering, Iowa State University, Ames. For improvements in real-time control and dynamic security assessment for electric power systems.

Darsh T. Wasan, vice president and Motorola Chair, Department of International Affairs, Illinois Institute of Technology, Chicago. For pioneering research, inspirational teaching, and the development of novel technology in colloidal processing and interfacial rheology.

Kaspar J. Willam, professor of civil engineering, University of Colorado, Boulder. For contributions to constitutive modeling and computational failure analysis of concrete and quasi-brittle materials and structures.

David C. Wisler, manager, University Programs and Aerotechnology Laboratories, GE Aircraft Engines, Cincinnati, Ohio. For advancing the understanding of multistage compressor flows and improving product blading designs.

Chien-Fu Jeff Wu, Coca Cola Chair in Engineering Statistics, School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta. For conceiving and building modern systems of experimental design based on contemporary methods of estimating parameters to improve quality.

Victor W. Zue, professor, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge. For advances in the understanding of acoustic phonetics and systems for understanding spoken language.

New Foreign Associates

Robin J. Batterham, chief technologist, Rio Tinto Limited, Melbourne, Australia. For the modeling of iron ore systems and team leadership in the development of innovative industrial metallurgical processes.

Manuel Elices, dean of materials science and engineering, Escuela de Ingenieros de Caminos–UPM, Madrid, Spain. For contributions to fracture mechanics of concrete at cryogenic temperatures and stress corrosion cracking of prestressed steel and for inspirational leadership.

Herbert Gleiter, director, Institute of Nanotechnology, Research Center Karlsruhe, Karlsruhe, Germany. For contributions to the theoretical and practical uses of nanostructured materials.

James A. Gosling, fellow and vice president, Sun Microsystems Inc., Menlo Park, California. For the conception and development of the architecture for the Java programming language and for contributions to window systems.

Tatsuo Izawa, president and chief executive officer, NTT Electronics Corporation, Tokyo, Japan. For the invention and perfection of the vapor axial-deposition method for the production of optical fibers.

Ludwik Leibler, professor of soft matter and chemistry, and director of research (1st Class) at CNRS, Ecole Superieure de Physique et Chimie Industrielles, Paris, France. For fundamental theoretical insights into the structure, self-assembly, and properties of polymer-based formulations.

Lennart Ljung, professor, Department of Electrical Engineering, Linkoping University, Linkoping, Sweden. For contributions to the understanding and practical uses of system identification theory and techniques.

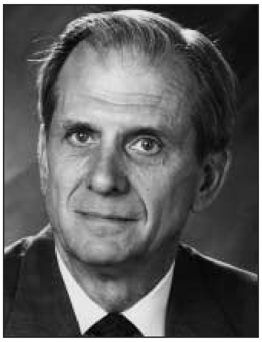
Herbert A. Mang, professor, Institute for Strength of Materials, Vienna University of Technology, Vienna, Austria. For contributions to computational mechanics of concrete and finite element analysis of reinforced concrete structures.

Pierre Perrier, secretary, French Academy of Technology, Paris. For major contributions to aircraft and computer-aided design.

Choon Fong Shih, president and vice chancellor, National University of Singapore, Singapore. For the development of innovative computational methods in nonlinear fracture mechanics and for international leadership in engineering.

John R. Willis, professor, Center for Mathematical Sciences, University of Cambridge, Cambridge, United Kingdom. For contributions to the micromechanics of engineering materials and the establishment of rigorous bounds on the properties of nonlinear composites.

Message from the Home Secretary



W. Dale Compton

Dear Colleagues,

The Membership Policy Committee (MPC) is in the midst of reviewing the NAE election process, especially the process by which slots for candidates are allocated and the treatment of nominations for interdisciplinary candidates. The MPC will make its recommendations to the NAE Council on February 11.

In addition, the articles of incorporation and bylaws are being updated. The proposed changes will be presented during the business session of the annual meeting on October 4, at which time members who are in attendance will be asked to vote. Members who do not attend will be given an opportunity to vote by mail. Details of the proposed changes will be mailed to all members approximately 30 days before the annual meeting.

As the 2004 membership elections draw to a close, I thought you would be interested in the demographics of the nominations and candidates whose names will appear on the ballot. We had a record number of nominations for the 2004 election—a total of 555 (309 of them new). Two-thirds of the candidates were also new nominations. The average age of nominees was just under 58 (50 for females and 54 for minority nominees). The average age of candidates was 58 (53 for females and 61 for minority nominees). Eighty-five percent of nominees and 77 percent of candidates had PhDs. Thirty-seven percent of nominees and 23 percent of candidates were naturalized citizens. Approximately 75 percent of the academic nominees had been honored with fellowships in professional societies; 36 percent of nominees in the business sector and 55 percent in other work sectors had fellowships. Fifty percent of academic candidates, 45 percent of business candidates, and 80 percent of other candidates had been honored with fellowships in professional societies. Eighteen percent of academic candidates, 21 percent of business candidates, and 9 percent of other candidates had only three references. The numbers for candidates were lower—10 percent for academics, 15 percent for business, and none for others.

These statistics are only marginally different from those reported last year. Thus, they appear to present a rather good description of the nomination and candidate selection process.

W. Dale Compton
Home Secretary

National Academy of Engineering

2003 Private Contributions

Gifts received between January 1 and December 31, 2003.

Golden Bridge Society

The Golden Bridge Society recognizes the generosity of current members who have made cumulative contributions of $20,000 or more, as well as planned gifts of any size.

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Simon Ramo
George B. Rathmann
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* Recently deceased

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Rosette Society

The Rosette Society recognizes members and friends who contributed $5,000 or more to the National Academies in 2003.

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Willis H. Ware
Edward Woll
A. Thomas Young

Friends

Thomas H. Grainger Jr.
Olga Kirchmayer

* Recently deceased

Charter Society

The Charter Society recognizes members and friends who contributed between $1,000 and $4,999 to the National Academies in 2003.

NAE Members

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NAE Senior Scholar-in-Residence

Donna J. Dean

Donna J. Dean, senior advisor for engineering to the director of the National Institutes of Health (NIH) and former deputy director of the National Institute of Biomedical Imaging and Bioengineering (NIBIB) at NIH, joined the NAE Program Office in January 2004 as senior scholar-in-residence. During her two-year residency, Dr. Dean will work with members and staff of the National Academies and representatives of federal agencies, academic institutions, and the private sector on issues at the interface of engineering and the life and health sciences.

As founding and acting NIBIB director (2000–2002) and deputy director (2002–2003), Dr. Dean played a leading role in planning, directing, and managing programs and resources, overseeing more than 800 funded grants and a budget of more than $281 million in fiscal year 2003. She was instrumental in filling key managerial and scientific staff positions and in establishing the National Advisory Council for Biomedical Imaging and Engineering. Concurrently, she was appointed NIH liaison to the National Institute of Standards and Technology and the U.S. Department of Health and Human Services (DHHS) regenerative medicine working group.

Dr. Dean was senior scientific advisor to the NIH director from 1998 to 2000. She was NIH/DHHS liaison to the congressionally mandated Commission on the Advancement of Women, Minorities, and Persons with Disabilities in Science, Engineering, and Technology Development, cochaired (with the surgeon general) the DHHS Chronic Fatigue Syndrome Coordinating Committee, was DHHS representative to the Working Group on Science and Technology of the President's Interagency Council on Women, and represented NIH on Gulf War issues. With Dr. Marianne Legato of Columbia University, she cochaired the Task Force to Update the National Research Agenda for Women's Health for the 21st Century.

Dr. Dean graduated from Berea College (Kentucky) with an undergraduate degree in chemistry and earned her Ph.D. in biochemistry from Duke University. In the following years, she was a visiting research fellow in the Department of Biology, Princeton University, a research chemist in clinical endocrinology at NIH, and a consumer safety officer with the Food and Drug Administration. She then spent 15 years with the NIH Division of Research Grants and its successor organization, the Center for Scientific Review. Dr. Dean is a member of the American Chemical Society, American Society for Investigative Pathology, American Society for Engineering Education, American Society for Cell Biology, Society of Women Engineers, and Society for the Advancement of Chicanos and Native Americans in Science. She is national treasurer of the Association for Women in Science and a fellow of the American Institute for Medical and Biological Engineering.

Japan-America Frontiers of Engineering Symposium

Michael Todd (University of California, San Diego) gives a presentation on state-of-the-art optical-based sensing. Session co-chairs Steven Glaser (University of California, Berkeley) and Muneo Hori (University of Tokyo) are seated at the table.

On November 20–22, NAE hosted the 2003 Japan-America Frontiers of Engineering (JAFOE) Symposium at the Beckman Center in Irvine, California. This was the third JAFOE symposium but the first one hosted by NAE (the first two were held in Japan). Approximately 60 engineers—30 from each country—participated. Guests from the National Academy of Engineering of Korea and the Chinese Academy of Engineering also attended the meeting with a view to starting similar programs in their countries.

The four topics at the meeting this year were: large-scale civil systems; electrifying the twenty-first century; systems biology and the emerging discipline of biological engineering; and multimedia networking. The presentations (by two Japanese and two Americans on each topic) included: the strategic maintenance of bridges of the Tokaido Shinkansen; distributed power generation and fuel cells; computer-based models and virtual patients; and large-scale streaming-video servers.

A high point of the symposium was the dinner speech given by **Robert W. Conn**, managing director of Enterprise Partners Venture Capital. Dr. Conn first described how his career as an engineer had evolved through positions in academia and industry and then provided an insightful look at the U.S. venture capital industry. Other highlights included poster sessions on the first afternoon that gave participants a chance to describe their technical work or research; a tour of the Jet Propulsion Laboratory and a presentation by Pete Theisinger, project manager of the Mars Exploration Rover; and a dinner hosted by **Thomas E. Everhart** at the Athenaeum at Caltech.

James G. Fujimoto, professor, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, and Kazuhiro Sakurada, principal investigator, Department of Frontier Medicine, Kyowa Hakko Kogyo Co., Ltd., cochaired the organizing committee and the symposium. JAFOE meetings are organized in cooperation with the Engineering Academy of Japan and the Japan Science and Technology

Forest White (MIT) and Akiko Futamura (Sumitomo Corp. Biosciences) discuss her poster at the JAFOE meeting.

Agency (JST). Funding was provided by JST, the U.S. Air Force, the Office of Naval Research International Field Office, and NAE. Plans are under way for a fourth JAFOE meeting on November 4–6, 2004, in Japan. An organizing committee, again chaired by Dr. Fujimoto and Dr. Sakurada, is planning the program. The topics for the next symposium will be biomedical instrumentation and devices, hydrogen energy, information technology for the elderly, and photonics.

FOE symposia, which bring together outstanding engineers from industry, academia, and government, give young engineers an opportunity to learn about cutting-edge research in many fields, which is increasingly important as engineering becomes more in-terdisciplinary. The meeting also facilitates the establishment of contacts and encourages collaboration among leaders of the next generation of engineers.

For more information about the symposium series or to nominate an outstanding engineer to participate in a future FOE meeting, contact Janet Hunziker at the NAE Program Office at (202) 334-1571 or by e-mail at *jhunziker@nae.edu*.

Calendar of Meetings and Events

February 11–12	NAE Council Meeting *Irvine, California*
February 12	NAE National Meeting *Irvine, California*
February 24	NAE Awards Dinner Ceremony and Presentation
February 25	NAE Finance and Budget Committee Conference Call
March 2	Grainger Prize Planning Meeting
March 5	NAE Congressional Luncheon
March 9	NAE Regional Meeting *San Jose, California*
March 25	NAE Regional Meeting *Houston, Texas*
April 1	Community College Pathways Committee Meeting
April 8	NAE Regional Meeting *Philadelphia, Pennsylvania*
April 15	NAE Regional Meeting *Columbus, Ohio*
April 28	Symposium on Technological Literacy for State Education Leaders
April 29–May 1	7th German-American Frontiers of Engineering Symposium
May 7	NAE Congressional Luncheon
May 13–14	NAE Council Meeting

All meetings are held in the Academies Building, Washington, D.C., unless otherwise noted. For information about regional meetings, please contact Sonja Atkinson at *satkinso@nae.edu* or (202) 334-3677.

Marian Koshland Science Museum

Global warming exhibit.

The Marian Koshland Science Museum of the National Academy of Sciences will open in Washington, D.C., in April 2004. The Koshland Science Museum will be the only museum in the nation's capital dedicated to exploring science and public policy decisions. The mission of the museum is to increase the public understanding and appreciation of the value of science addressed in reports by the National Academies. The museum is intended to appeal to adults and children over the age of 13.

The museum will have three exhibit areas, one of which will be "The Wonders of Science," a permanent exhibit that will be regularly updated to present current, often controversial, scientific issues. State-of-the-art displays, interactive exhibits, videos, and the latest scientific projections will focus on advancements that impact daily life, giving visitors a basis for making informed decisions about science-related public policy decisions and science-related news stories.

The inaugural exhibits in the other two areas will focus on DNA and global warming, with interactive displays designed to give visitors a sense of the frontiers of current research, an opportunity to learn about the potential effects of global warming, and information about how DNA analysis can be used to catch criminals, stop epidemics, and prevent diseases. The global warming and DNA exhibits will be on view for approximately two years, after which they will travel to other museums across the country.

Probe the Sequence interactive exhibit.

In Memoriam

WILLIAM D. ALEXANDER, 92, consultant, died on December 9, 2003. Mr. Alexander was elected to NAE in 1978 for his leadership in organizing complex multidisciplinary engineering.

CHARLES CONCORDIA, 95, General Electric Company (retired) and private consulting engineer, died on December 25, 2003. Dr. Concordia was elected to NAE in 1978 for contributions to the field of analysis of rotating equipment and power system performance, control, and reliability.

WILBUR B. DAVENPORT, 83, professor of communications science and engineering, emeritus, Massachusetts Institute of Technology, died on August 28, 2003. Dr. Davenport was elected to NAE in 1975 for his contributions to communications engineering and education and for his leadership in continuing engineering education.

DAVID S. LEWIS JR., 86, retired chairman and chief executive officer, General Dynamics Corporation, died on December 15, 2003. Mr. Lewis was elected to NAE in 1971 for his contributions to aerospace management in the conception, development, and production of aircraft and spacecraft.

GEORGE F. MECHLIN, 80, retired vice president, research and development, Westinghouse Electric Corporation, died on December 12, 2003. Dr. Mechlin was elected to NAE in 1971 for engineering contributions to national, strategic, underwater missile and ocean engineering systems, including Polaris and Poseidon launchers and submarine nuclear reactors.

BRUCE S. OLD, 89, president, Bruce S. Old Associates Inc., died on September 3, 2003. Dr. Old was elected to NAE in 1968 for contributions to process improvements in iron and steel, metallurgy of nuclear materials, and cryogenics.

CHARLES J. PANKOW, 80, chairman, Charles Pankow Builders, died on January 12, 2004. Dr. Pankow was elected to NAE in 1977 for his contributions to the application of innovations in construction engineering.

FREDERICK G. POHLAND, 72, professor and Edward R. Weidlein Chair of Environmental Engineering, University of Pittsburgh, died on January 9, 2004. Dr. Pohland was elected to NAE in 1993 for advancing the theory of anaerobic treatment processes and their applications to solid waste management.

WILLIAM C. REYNOLDS, 70, professor of mechanical engineering, emeritus, Department of Mechanical Engineering, Stanford University, died on January 3, 2004. Dr. Reynolds was elected to NAE in 1979 for the development of theoretical bases for convective heat transfer analysis and contributions to fluid mechanics.

CHESTER P. SIESS, 87, professor emeritus of civil engineering, University of Illinois, died on January 14, 2004. Dr. Siess was elected to NAE in 1967 for research in reinforced concrete construction.

THOMAS G. STOCKHAM JR., 70, professor emeritus, University of Utah, died on January 6, 2004. Dr. Stockham was elected to NAE in 1988 for his contributions to the field of digital audio recording.

ARTHUR R. VON HIPPEL, 105, Institute Professor Emeritus and retired director, Laboratory for Insulation Research, Massachusetts Institute of Technology, died on December 31, 2003. Dr. von Hippel was elected to NAE in 1977 for pioneering research in molecular engineering and for setting a pattern for interdisciplinary materials research.

The National Academies Update

Program to Improve Roadway Safety and Efficiency

Adverse weather is associated with more than 1.5 million vehicle accidents each year, resulting in about 800,000 injuries and 7,000 deaths. In addition, drivers endure more than 500 million hours of weather-related delays annually. Hurricanes, blizzards, and flash floods also create logistical challenges—for example, choosing evacuation routes or deciding when to close roads—for traffic managers, law enforcement officials, and emergency managers.

A new report from the National Research Council recommends that the federal government establish a research program led by the Federal Highway Administration (with the National Oceanic and Atmospheric Administration) to coordinate efforts by the weather and surface-transportation research communities. Regional research centers should be established to develop new technologies for monitoring, predicting, and communicating the effects of weather on road conditions, and national demonstration corridors for testing should be established along two U.S. interstate highways. The estimated cost of the program would be about $25 million per year for 15 years.

NAE members on the report committee were **Francis B. Francois**, independent consultant and retired executive director, American Association of State Highway and Transportation Officials, and **Margaret A. LeMone**, senior scientist, National Center for Atmospheric Research. Copies of *Where the Weather Meets the Road: A Research Agenda for Improving Road Weather Services* will be available later this year from the National Academies Press, tel. 202-334-3313 or 1-800-624-6242 or online at *http://www.nap.edu*.

Improving NSF's Ranking of Proposals and Project Management

Large research facilities are a vital component of the National Science Foundation's (NSF's) science and technology portfolio. New facilities might include more powerful versions of instruments that have been used for decades, such as telescopes, or new ways of gathering information, such as a project to measure gravity waves generated by cosmic events. In 1995, NSF created the major research equipment and facilities construction (MREFC) account to support the construction of large research facilities. In recent years, plans for such facilities have increased, and approved projects have become increasingly complex and expensive.

A new National Academies report recommends improvements to NSF's processes for identifying, developing, prioritizing, and managing projects funded through MREFC. Although MREFC projects account for just under 4 percent of NSF's total budget, they are highly visible because they have multimillion dollar budgets, can potentially determine the course of research, and bring economic benefits to the regions where they are located. However, many researchers and federal policy makers have expressed concerns about NSF's current methods of selecting projects for funding.

The proposed strategy includes creating and implementing a road map for selecting facilities that would be used by the National Science Board, which helps oversee NSF, to rank projects proposed for funding. The road map would inform both NSF's annual budget submission to Congress for MREFC funding and its overall budget requests. The report also recommends that the road map be revised periodically to reflect scientific advances and changes in policy.

NAE members serving on the study committee were **David Auston**, president, Kavli Foundation, and **William Friend**, executive vice president (retired), Bechtel Group Inc., and chair, University of California President's Council on National Laboratories. Copies of *Setting Priorities for Large Research Facility Projects Supported by the National Science Foundation* are available from the National Academies Press, tel. 202-334-3313 or 1-800-624-6242 or online at *http://www.nap.edu*.

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at <*http://www.nap.edu*> or by phone at (800) 624-6242. *(Note: Prices quoted by NAP are subject to change without notice. Online orders receive a 10 percent discount. Please add $4.50 for shipping and handling for the first book and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)*

Effectiveness of Air Force Science and Technology Program Changes. In recent years, Congress and others have expressed concerns about several aspects of the overall Air Force science and technology (S&T) program. In the FY2002 National Defense Authorization Act (P.L. 107-107), Congress mandated a study by the National Research Council of the effectiveness of changes in that program undertaken by the Air Force in response to those concerns. This review focuses on actions taken by the Air Force to improve management of its science and technology (S&T) programs and assesses whether program changes instituted by the Air Force since 1999 are sufficient to ensure the availability of the technology necessary to maintain U.S. military superiority. Paper, $18.00.

Review of NASA's Aerospace Technology Enterprise: An Assessment of NASA's Pioneering Revolutionary Technology Program. The Aeronautics and Space Engineering Board of the National Research Council is in the midst of a series of studies to review the National Aeronautics and Space Administration (NASA) Aerospace Technology Enterprise for NASA and the Office of Management and Budget. In this report, the second in the series, the study committee addresses a series of questions, posed by NASA, about the structure and quality of its three aeronautics technology programs: vehicle systems, airspace systems, and aviation safety. The report provides recommendations to guide Congress, the administration, and NASA in setting priorities for NASA's aeronautics R&D programs, as well as findings and recommendations for improvements at the program and project levels. Paper, $31.00.

Assessment of Directions in Microgravity and Physical Sciences Research at NASA. For 30 years, the National Aeronautics and Space Administration (NASA) microgravity program has used space as a laboratory for studies of basic phenomena in combustion, fluid dynamics, materials science, and fundamental physics. This report examines the scientific and commercial impact of NASA's past microgravity research, recommends future research in the most promising areas in each field, and proposes guidelines for setting priorities among the recommended areas. Each proposal should be assessed in terms of its likelihood of success and the magnitude of its potential impact on: (1) scientific knowledge and understanding; (2) terrestrial applications and industry needs; and (3) NASA's technology needs. At NASA's request, the report also includes a review of emerging fields of research, such as nanotechnology and biophysics, and recommendations as to which topics from those fields might be suitable for integration into NASA's microgravity program. Paper, $28.25.

Assessing Research-Doctorate Programs: A Methodology Study. How should information about the quality of research-doctorate programs be assessed and presented? The approach to assessing doctoral programs presented in this report will be useful to administrators, faculty, and others with an interest in improving the education of Ph.D.s in the United States. The report includes a review of the methodology used for the 1995 National Research Council rankings and recommends changes, including the collection of new data about Ph.D. students and additional data about faculty, as well as new techniques for presenting qualitative data on doctoral programs. The report also recommends that the taxonomy of fields used in the 1995 rankings be revised. Paper, $35.00.

Building an Electronic Records Archive at the National Archives and Records Administration: Recommendations for Initial Development. This report examines the role of the National Archives and Records Administration (NARA) in the archiving and preservation of federal records, including digital records, such as e-mails and websites. The report provides both an assessment of NARA's current activities and recommendations for the Electronic Records Archive (ERA) Program. Separate chapters address commonalities between requirements for the ERA and other activities, lessons to be learned from demonstration projects, a strategy for evolution and acquisition, and other topics. Paper, $18.00.

Critical Issues in Weather Modification Research. This report provides an authoritative discussion by a committee of experts of the scientific basis for weather modification in the United States. The committee concludes that a coordinated national research program is called for to answer fundamental questions about basic atmospheric processes and to address ways to overcome barriers to progress in weather modification. Paper, $33.00.

Cybersecurity of Freight Information Systems: A Scoping Study: Special Report 274. The U.S. Department of Transportation (DOT) requested that the National Research Council (NRC) of the National Academies form a committee to develop an approach to establishing an inventory of information, computer, and communications applications in freight transportation and assessing the vulnerabilities of information systems to disruptions by criminals and terrorists. NRC formed the Committee on Freight Transportation Information Systems Security under the auspices of the Transportation Research Board and the Computer Science and Telecommunications Board to conduct the study. In the interim, the federal government moved the Transportation Security Administration to the Department of Homeland Security (DHS), along with many security functions that were formerly performed by DOT. Thus, many of the committee's recommendations and comments are applicable to both DOT and DHS. The report outlines options for a full assessment of the challenges to cybersecurity in freight transportation information systems and the development of a strategy to reduce vulnerabilities to cyberattacks. Available from the Transportation Research Board at *http://trb.org/trb/bookstore/*, tel. (202) 334-3213. Paper, $21.00.

Enabling Ocean Research in the 21st Century: Implementation of a Network of Ocean Observatories. To understand changes in the ocean and to provide a scientific basis for addressing concerns about climate change, natural hazards, and the health and viability of living and nonliving resources along our coasts and in the open ocean, scientists must move beyond traditional expeditionary modes of investigation to observation systems for studying processes in the ocean basins over varying temporal and spatial scales. This report evaluates the scientific and technical readiness for the establishment of a research-driven network of ocean observatories. The report also highlights outstanding issues: the status of planning and development; factors that affect the timing of construction and installation; the cost of and requirements for maintenance and operations; the need for sensor development and data management; the availability of ships and deep-submergence facilities; and the role of research-based observatories in operational or planned national and international ocean observing systems. Paper, $49.00.

End Points for Spent Nuclear Fuel and High-Level Radioactive Waste in Russia and the United States. This analysis of the management of spent nuclear fuel and high-level radioactive waste in Russia and the United States includes inventories, approaches, and end-point options for storage and disposal. The committee finds that, despite differences in philosophy about nuclear fuel cycles, Russia and the United States need similar kinds of facilities and face similar challenges, although many of the problems are worse in Russia, and funding is less available there. The report recommends (1) immediate and near-term actions, such as measures for protecting and stabilizing materials that pose security and safety hazards, and (2) longer term measures, such as increasing interim storage capacity and studying the effects of deep injection. The report also points out other areas for collaboration. Paper, $33.75.

Environmental Cleanup at Navy Facilities: Adaptive Site Management. In this report, the concepts of adaptive management are applied to complex, high-risk, hazardous-waste sites typical of contaminated military, Environmental Protection Agency, and other sites. The report suggests ways of moving forward at sites with recalcitrant contamination where cleanup efforts have stalled. The recommendations include more rigorous data collection and analysis, considerations of alternative treatment technologies, and comprehensive, long-term stewardship of these sites. Paper, $45.00.

Improving the Scientific Basis for Managing DOE's Excess Nuclear Materials and Spent Nuclear Fuel. This study, prepared for the U.S. Department of Energy (DOE) Environmental Management Science Program, points out opportunities for basic research that might lead to new approaches to storing, reusing, or disposing of surplus materials from former DOE production operations. The report addresses plutonium-239, spent fuels, cesium-137, and strontium-90 capsules stored at Hanford, Washington, as well as depleted uranium and higher actinide isotopes. The study recommends that research be focused on ensuring the safe storage of, and finding new uses for, materials that cannot be reproduced in the quantities available in the current inventory. Paper, $28.75.

Information and Communications: Challenges for the Chemical Sciences in the 21st Century. The Workshop on Information and Communications was the third in a series of six workshops that comprise a larger study, Challenges in the Chemical Sciences in the 21st Century. This workshop focused on the mutual growth and interdependence of the chemical sciences and information communities. The chemical enterprise has provided information technology (IT) with device-fabrication processes and new materials and methods. IT, in turn, has provided the chemical sciences with resources for computations, communications, and data management. One finding that arose out of the workshop presentations was that a strong infrastructure at the intersection with IT will be critical to the success of research in chemical sciences and technology. The intersection represents a frontier that has great potential, but substantial technical progress will require additional resources for research, education, and infrastructure. Paper, $43.00.

Living on an Active Earth: Perspectives on Earthquake Science. The destructive force of earthquakes has stimulated human inquiry since ancient times, yet the scientific study of earthquakes is a surprisingly recent endeavor. The first instrumental recordings of earthquakes were made in the second half of the nineteenth century, and the primary mechanism for generating seismic waves was identified in the early twentieth century. Despite its recent beginnings, the science of earthquakes has developed into a vigorous discipline based on a wide range of laboratory, field, and theoretical investigations. At the level of basic science, it provides a comprehensive understanding of earthquake behavior and related phenomena in the Earth and other terrestrial planets. At the level of applied science, it provides a knowledge base of great practical value for a global society whose infrastructure is built on the Earth's active crust. This report describes the growth and origins of earthquake science and identifies research and data collection that will strengthen the scientific and social contributions of this exciting new discipline. Hardback, $59.95.

Managing Carbon Monoxide Pollution in Meteorological and Topographical Problem Areas. The regulation of carbon monoxide has been one of the great success stories in air pollution control. In 1971, more than 90 percent of the locations with carbon monoxide monitors were in violation of regulatory standards. Today only a few monitors show violations, on a small number of days and mainly in areas with unique meteorological and topographical conditions. This report reviews the progress to date and recommends steps for the future. Paper, $50.00.

The Measure of STAR: Review of the U.S. Environmental Protection Agency's Science to Achieve Results (STAR) Research Grants Program. This favorable review of the U.S. Environmental Protection Agency's (EPA's) competitive research grants program finds that the program has yielded significant new information critical to EPA's decision-making processes. Established in 1995, the grants program was designed to enable the nation's best scientists and engineers to explore ways to safeguard the environment and protect public health. The program awards about $100 million a year in grants and fellowships to independent investigators, multidisciplinary teams, and graduate students at universities and nonprofit institutions. Paper, $40.00.

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