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The Air Force: Science, Technology, and Transformation

by Donald C. Daniel

Overview

A unique connectivity exists in the Air Force between science, technology, and transformation. From the defining moment of powered flight in 1903 to the creation of the Air Force as a separate service in 1947 to the present, these three elements have been continuously linked and undoubtedly will remain so.

This paper provides a brief historical perspective of the ties between science, technology, and transformation in the earliest days of the Air Force; gives an overview of current Air Force science and technology; offers a look at five future transformational capabilities—unmanned combat aerial vehicles, small munitions, directed energy weapons, microsatellites, and the joint battlespace infosphere—that demonstrate the strong nature of the link today; and lastly, presents some challenges and issues.

Historical Perspective

The Air Force is the youngest of the Nation's armed services. It was formed in 1947 in the aftermath of World War II, having previously been a branch of the Army as the Army Air Corps. A number of influences, perhaps the most profound of which are strategic bombardment, nuclear weapons, intercontinental ballistic missiles, and space flight, have been crucial in forming and sustaining the Air Force as an institution. Each of these developments, all of which involved long-range flight, distinguished the Air Force from the other services.

Like the other services, however, the Air Force was built on the shoulders of giants. The men most closely associated with its continuing transformation are Henry Arnold, Theodore von Karman, and Bernard Schriever (see brief biographies of each on the following page). General Arnold was the founding father of the Air Force who, working closely with von Karman, set the tone for the highly technical nature of this service. Von Karman, the world's leading aeronautical scientist in the mid 20th century, was a strong advocate of close ties between the military and science. General Schriever, the driver behind the initial movement of the service toward intercontinental ballistic missiles and space flight, sustained and perhaps institutionalized the highly technical nature of the Air Force.

Air Force Science and Technology

Science and technology are often approached as a singular event, and they even appear as a single line item in the Air Force modernization budget. This item (or event) is a large one, however, and typically, at more than $1.5 billion, is one of the top half-dozen programs (of a list that might run two pages or more) per year.

At the next level of specificity, Air Force science and technology comprises over 20 different program elements. These elements include 1 for basic research and approximately 10 each for applied research and advanced technology development, the latter 2 categories being aligned with specific technical areas of relevance to the Air Force. Continuing down to the bench level, thousands of individual projects are under way at any given time.

The Air Force science and technology program is highly leveraged with a wide variety of grants, contracts, partnerships, and alliances. Participants include in-house scientists and engineers, universities, industry, and international organizations. Science and technology is long term in its nature. In spite of our current fascination with the apparent rapid pace of information technology, it is not unusual for many elements of science and technology to see research and development at fundamental levels for 20 years before a product publicly emerges. The sustaining nature of the service laboratories is one of the great strengths for the Department of Defense, often serving as the launch point for large-scale activities by the Defense Advanced Research Projects Agency (DARPA) and/or industry. Success is not guaranteed in the science and technology business; failure is part of the learning and discovery process.

Figure 1 shows the hierarchical building blocks of research and development. Science and technology is a subset of the overall research and development process. In budgetary terms, the Air Force research and development program includes projects with a total value of tens of billions of dollars annually. The science and technology subset of this is currently on the order of $1.5 billion annually.

Three Air Force Visionaries

General Henry H. ("Hap") Arnold (1886–1950) is unquestionably the father of the Air Force. A 1907 graduate of West Point who ranked closer to the bottom of his class than the top, he was taught to fly by the Wright brothers at Huffman Prairie (now part of Wright-Patterson Air Force Base, Ohio) and earned the first military aviator's badge. A protégé of Billy Mitchell, an extremely vocal, early advocate of air power, Arnold rose steadily through the ranks to become Chief of the Army Air Corps in World War II. In 1944, he was promoted to five-star rank as General of the Army. When the Air Force was created as a separate service after Arnold had retired, he was made General of the Air Force by an act of Congress. He is the only person in Air Force history to date to achieve this rank.

Shortly before World War II, Arnold sought out and met Theodore von Karman and started a professional relationship with him that was vital to linking science and technology to the Air Force. Possibly influenced by his early experiences with the Wright brothers or Billy Mitchell—or by von Karman's reputation as the world's foremost aerodynamicist—Arnold initiated contact with von Karman and maintained it for the remainder of his life.

In 1944, Arnold reached a profound conclusion that would forever link the future Air Force to science and technology. Specifically, he concluded that the most important lesson coming out of the war for future air forces was that national security could only be provided by preeminence in research. Subsequently, he tasked von Karman to lead a study to "look into every science and find basic developments that could make U.S. airpower invincible."

Theodore von Karman (1881–1963) was born in Budapest, Hungary. He studied under Ludwig Prandtl, the world's foremost aerodynamicist at the time, in Goettingen, Germany, receiving a doctorate in this specialty. He then moved to Aachen, Germany, where he subsequently supplanted his teacher and mentor as the world's foremost aerodynamicist, deriving, among other things, modern supersonic aerodynamic theory.

In the late 1920s, the California Institute of Technology began pursuing von Karman to lead its newly established Guggenheim Aeronautical Laboratory. Von Karman immigrated to the United States in 1930 to lead this laboratory. In the following years, he taught, conducted research, and built a broad following of graduate students, many of whom would become national leaders in prominent government and academic organizations. He also worked closely with the emerging aeronautical industry that was being attracted to southern California. In this latter role, he founded the Jet Propulsion Laboratory and was instrumental in the founding of Aerojet General Corporation.

Von Karman and Arnold met in the late 1930s and formed a bond that lasted until Arnold's death in 1950. *Toward New Horizons* (the study that resulted from Arnold's tasking of von Karman in 1944), more than any other single event, formed the vision for the nascent U.S. Air Force. The lead essay by von Karman, "Science, The Key to Air Supremacy," became the service blueprint. Von Karman's famous statement first appeared in this essay: "Scientific results cannot be used efficiently by soldiers who have no understanding of them, and scientists cannot produce results useful for warfare without an understanding of operations."

General Bernard Schriever (b. 1910), although not as well known as Arnold and von Karman, had an impact on the Air Force that is perhaps as significant. Born in Bremen, Germany, he immigrated to the United States as a boy. Educated at Texas A&M and Stanford in engineering, he was a bomber pilot in World War II, seeing combat in the Pacific.

After the war, Schriever was assigned to the Pentagon, where he became involved in scientific aspects of the newly created Air Force. He later graduated from the National War College in Washington, DC, and was sent to southern California to establish a small office for the development of intercontinental ballistic missiles (ICBMs) and space systems. He subsequently led the development of every Air Force ICBM that found its way into production or set the stage for later development. During this time, he also led the development and deployment of many of the early defense space systems.

Schriever was an extremely forceful personality and, like most agents of change, got his way more often than not. He continued to rise in rank, ultimately reaching four stars as the Commander of Air Force Systems Command. Although Schriever was not instrumental in the initial linkage of science and technology to the core of the Air Force, he was vital in sustaining and institutionalizing it.

The Air Force Research Laboratory (AFRL) manages the Air Force science and technology program. As shown in figure 2, AFRL consists of 10 technical directorates:

- Air Force Office of Scientific Research (AFOSR)
- Air Vehicles
- Directed Energy
- Human Effectiveness
- Information
- Materials and Manufacturing
- Munitions
- Propulsion
- Sensors
- Space Vehicles.

The entire basic research program is managed by AFOSR. Each of the technical directorates manages a portfolio of applied research and advanced technology development in its area of expertise.

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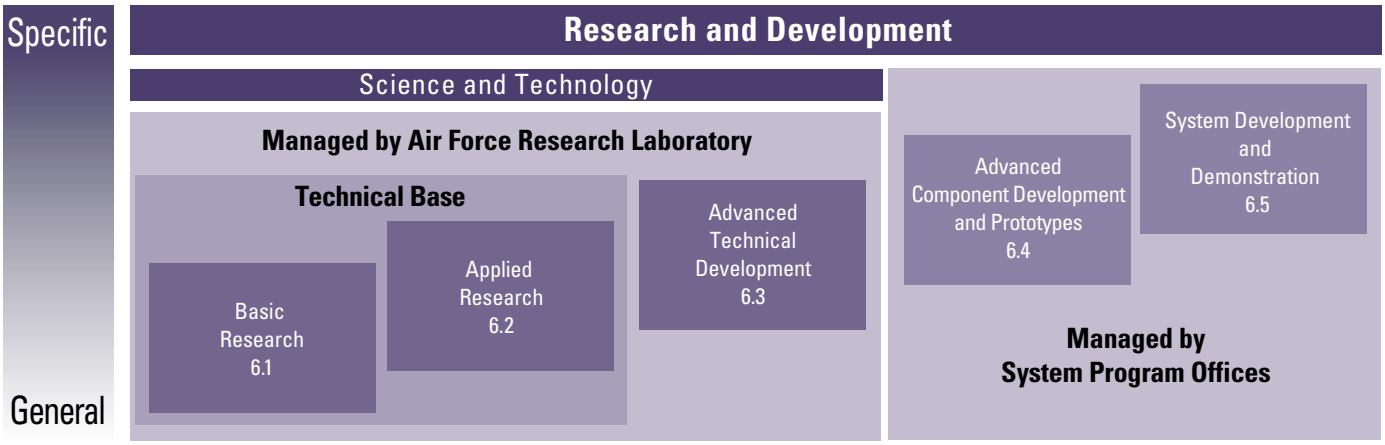
Figure 1. Air Force Research and Development



Future Capabilities

Five technology areas represent future transformational capabilities. Imagine a future battlefield where unmanned combat aerial vehicles (UCAVs), small munitions, directed energy weapons, microsatellites, and a joint battlespace infosphere are all operational and functioning. The provided capability and flexibility of these technologies are perhaps unprecedented. They are also well suited for the projected asymmetric world.

Unmanned Combat Aerial Vehicles. Nowhere in the Air Force are science, technology, and transformation more evident than in the X–45A UCAV. This joint DARPA/Air Force/Boeing program has produced two vehicles that are currently undergoing flight-testing at the National Aeronautics and Space Administration (NASA) Dryden Flight Research Center adjacent to Edwards Air Force Base, California.

The X–45A is 26 feet long, 7 feet tall, has a 33-foot wingspan, and has a gross takeoff weight of approximately 12,000 pounds. It is designed for high subsonic flight at medium to high altitudes to demonstrate the core functioning of the UCAV system. Subsequent models of the X–45 will be much larger and feature a mission radius of over 1,000 nautical miles.

The operational X–45 features two bomb bays with an internal weapons capacity of approximately 4,500 pounds. It is designed to carry a variety of munitions, including the 800-, 1,000-, and 2,000-pound joint direct attack munition (JDAM) and small diameter bomb. In addition, recent speculation includes some discussion of directed energy and support-jamming roles for UCAVs in the future.

The UCAV program emphasizes low production cost. The two X–45A vehicles were built at single assembly stations and feature composite airframes with large individual sections, no vertical tail, and removable wings. The entire vehicle was designed to fit within shipping containers for storage and deployment via C–17 transport aircraft. Although this is no longer part of the operational concept, the program still has aggressive cost reduction goals.

The current flight test program emphasizes software, communications, and man/machine interface. Building a flightworthy unmanned vehicle is no longer a significant challenge. However, building a fleet of such vehicles that can operate within the context of a modern airborne strike package certainly is.

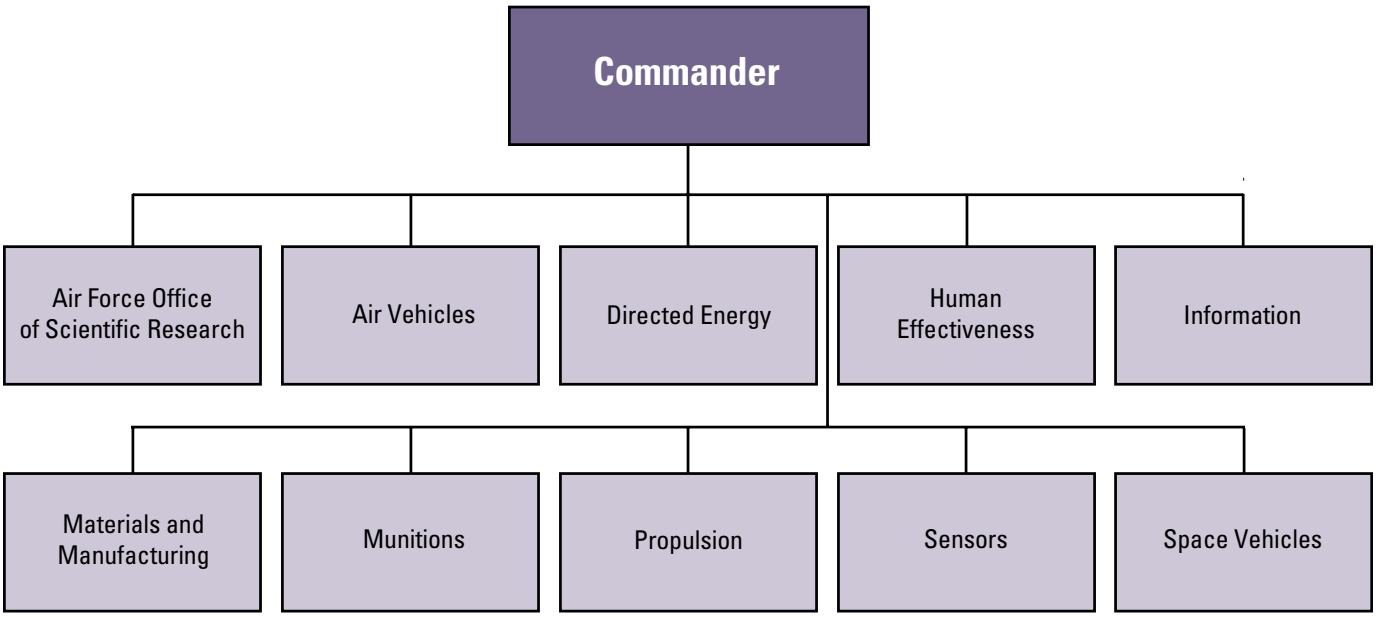
Small Munitions. The Air Force is committed to internal carriage of munitions for all emerging aircraft (F/A–22, F–35, and X–45). The resulting advantages in performance and low observability are obvious. A key challenge is keeping aircraft size/weight to a minimum, as there is a direct relationship between size/weight and cost. Small munitions are essential for achieving minimum size and accomplishing the mission with high-performance aircraft. Small munitions also result in more individual weapons available per aircraft per sortie.

The small diameter bomb is the first of the small munitions that will be available. With a length and diameter roughly half that of a 2,000-pound JDAM and a weight approximately one-tenth of this larger munition, it is easy to see how this new munition will be in high demand. Changes such as these make this a truly transformational step, not an evolutionary one.

The small diameter bomb features a host of established and developing subsystem technologies. These include a miniaturized anti-jam global positioning system (GPS)/inertial navigation system guidance, multievent hard target fuze, high-strength steel penetrator warhead, compact range extension kit, and laser radar seeker. The first three of these technologies will be incorporated into the initial model of the munition, with the latter two most likely in subsequent models. This initial combination of technologies will enable the Air Force to engage multiple targets per sortie with high probabilities of hit and kill. The range extension kit will offer considerable additional downrange and crossrange capability. The laser radar seeker will provide additional capability against ground mobile targets.

Additional small munition technologies being developed will also lead to miniaturized air-launched missiles suitable for internal carriage in similar platforms as those for the small diameter bomb. These munitions may be as small as 30 inches long and 8 inches in diameter. In addition to the laser radar seeker mentioned above,

Figure 2. Air Force Research Laboratory



these missiles might feature automatic target recognition algorithms, air-breathing propulsion, and multimode warheads capable of forming long rod penetrators, slugs, or fragments, depending on target hardness. Small munitions of this type may be particularly attractive for attacking mobile, time-critical targets.

Directed Energy Weapons. These weapons of interest fall into two categories: high-energy lasers and high-power microwaves. Of the two, the research into high-energy lasers is more mature and approaching application. The relative maturity of both is the result of decades of research, quite often at the component level.

Air Force research in high-energy lasers can be traced to the 1970s with the conceptual design of the Airborne Laser Laboratory. This research continued for approximately a decade, resulting in a flying laboratory (a modified Boeing 707) that demonstrated the ability to shoot down small missiles.

As work continued in this area, the Air Force created a considerable infrastructure for its research, focusing on the design of large chemical lasers. The chemical oxygen iodine laser was invented in the late 1970s, followed a decade later by the supersonic chemical iodine laser. The infrastructure continued to expand with the construction in the late 1980s of the starfire optical range, which was created for atmospheric compensation research. The Air Force also began a detailed series of worldwide atmospheric measurements in the late 1980s and early 1990s, along with research in adaptive optics. All of these technologies are critical in maintaining a tight laser cross-sectional diameter at extended ranges—an essential feature for weaponizing a high-energy laser.

After more than 20 years of research and a science and technology investment of over $1 billion, the Boeing 747–400, which will become the first airborne laser (ABL) aircraft, took flight in the summer of 2002. An extensive test program will be conducted for approximately 4 years, culminating with the shootdown of a boosting ballistic missile. Additional ABLs will then be built and will become part of the U.S. layered missile defense capability.

Another form of directed energy that is being weaponized has been disclosed recently under the name *active denial.* This technology features a high-power millimeter wave device being developed for nonlethal applications against enemy personnel. A laboratory demonstration device that features a powerful, efficient millimeter wave source, high-gain antenna, and generator/lithium ion battery power system has been assembled and tested to ranges beyond those of small arms. The demonstrator is not suitable for airborne application at this stage due to its size and weight; however, continuing research may enable this option in the future. In addition, other future high-power microwave devices may have potential application from UCAV platforms.

Microsatellites. Microsatellites (those weighing less than 100 kilograms) have the potential to transform military space activities and missions. The potential benefits are multiple and include significantly lower cost to orbit, enhanced tactical flexibility for battlefield commanders, and reduced vulnerability. These small satellites could eventually replace larger ones that perform well-established missions (such as global positioning), and they will enable new missions in

(such as global positioning), and they will enable new missions in logistics, space control, and multimission satellite clusters.

Microsatellites are a result of research in a variety of subsystem technologies. The enabling microsatellite technologies include multifunctional structures for cableless power buses, integrated power management, and lightweight interconnects; microelectromechanical systems for gyroscopes, scanning mirrors, and motors; transmit/receive antenna modules for electronic steering arrays; ultralight, thin film photovoltaic solar cells for energy storage; micropropulsion using small impulse charges for fine control of satellite constellations; automatic satellite docking mechanisms; and radiation-hardened electronics.

A key element in developing these subsystems is the ability to conduct space experiments. Although simulation and experiments conducted on the ground are valuable, certain aspects of technology must be demonstrated on orbit. This is particularly true when several subsystems are integrated for the first time or when multiple elements must be tested simultaneously. A good example of an on-orbit experiment that has been conducted recently is the AFRL MightySat II. Launched in July 2000, this low-cost, adaptable platform featured seven experiments, the most notable of which was a Fourier transform hyperspectral imager. The platform was active for over a year and provided excellent data during that time. Another currently active experiment is the Materials on International Space Station Experiment, which is a multiple venture involving NASA, the Air Force, and others. This experiment features dozens of material samples that are attached to the exterior of the International Space Station and allows for simultaneous, long-term evaluation of all of the materials under the same space conditions. Future planned experiments include a microsatellite that will perform fully autonomous proximity operations around a U.S. space object and a three-satellite formation that will begin to investigate the concept of a virtual satellite formed by a network of co-orbiting individual satellites.

Joint Battlespace Infosphere. No look into any element of military science, technology, and transformation would be complete without the consideration of information technology as it relates to command and control. The centerpiece of the Air Force science and technology effort in this area is the joint battlespace infosphere (JBI). The aim of this research is to evolve methods continuously for presenting effective battlefield information to decisionmakers at multiple levels. This involves a globally interoperable approach that aggregates, integrates, fuses, and disseminates relevant information.

JBI can be envisioned as a federation of multiple servers, resting on a global grid and forming a virtual information space that all users and systems can easily tap (using open-standard protocols) to exchange information. It will yield rapidly deployable, agile information architectures that are also built for rapid technology insertion. JBI should be thought of as a framework of information science and technology, not a specific product. The framework will, in fact, produce multiple products.

The JBI science and technology program features a combination of software and hardware design/evaluation activities. These activities focus on:

- design and evaluation of various technical approaches for performing publish-subscribe-query functions
- design and development of small software programs (fuselets) that will aggregate, integrate, and disseminate relevant battlespace information from distributed databases and different command and control systems
- designs to bring organizational units (and their information systems) into and out of JBI within hours
- design, testing, and integration of information assurance technology.

Some Challenges and Issues

Bringing the technologies discussed above to fruition is not without challenges and issues. Some of these are discussed below. It is also important to note that the technologies will evolve over different times and will not come into operational use simultaneously. Finally, one must be aware that new technologies almost certainly will require new tactics if they are to be fully utilized. This mutual evolution of technology and tactics is an absolute essential for true transformation.

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UCAV roles and missions are still being discovered and defined. Our ability to build and fly machines such as these has already been demonstrated and is clearly feasible technically. Our ability to go to war with them, especially as part of a modern airborne strike package, is in its infancy and will require time, perhaps a decade, to evolve. The central technologies will not be aerodynamics, propulsion, weapons, or sensors, but rather the information technologies associated with software and command and control. Human interaction will continue to be a key technical issue. The number of vehicles controlled by a single operator and the degree of vehicle autonomy authorized will require continuing experimentation and feedback loops between technologists and operators. The Air Force will continue to pay close attention to the cost of UCAVs. Production UCAVs will most likely not be exact replicas of the current X–45A. The desire for more range and extended duration flight times will drive up size and weight. Again, history has shown that size/weight and cost are closely related; increases in the former invariably result in increases in the latter. This will be a continuing challenge for UCAVs.

Small diameter bombs are the most mature of the technologies discussed herein. GPS-guided munitions of this type are well on their way to being fielded and will be a key part of future warfare involving the F/A–22, F–35, and UCAV. Miniature air-launched missiles, however, are another matter. The issue here revolves more around sensor and information technology than the traditional flight sciences. At the heart of the issue is the degree of autonomy that these weapons will have. Continued flight experimentation, at a more significant rate than has been done in the past, is required for perhaps several more years before Air Force officials will have the necessary

confidence in the critical automatic target recognition algorithms. Ultimately, the cost of these vehicles may also be a significant issue.

The Nation's first airborne directed energy weapons system—ABL, with its large chemical laser—is well on its way to being fielded. Looking to the future, the greatest technical challenge for weapons of this class will be the development of smaller, yet very powerful, lasers. Many experts think that this future lies with solid-state lasers. Moving in this direction will not only reduce the size of the flying platform but also greatly simplify the logistics tail (and cost). The key technical challenge undoubtedly will be achieving the needed high power levels. Achieving sufficiently small size and light weight while producing sufficient power will also remain a significant challenge for high power microwave (HPM) devices. As with lasers, HPM devices will have a variety of potential missions for different power levels. These range from disruption in the lower power ranges to destruction in the higher. Weaponization of directed energy will evolve over decades, and as these capabilities and a potential market materialize, industry capabilities will need to evolve. This is perhaps one technical area where the government/industry capability is not well balanced.

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The Air Force and its contractors have the ability to build and place on orbit individual functioning microsatellites, and their potential may be somewhat analogous to UCAVs. It is known that they can be built; now one must learn to fly and fight with them. This is especially true when considering multiple microsatellites that combine to conduct given missions. Some even envision swarms of such satellites. The resulting communications, information sharing, and orbital mechanics challenges for such an arrangement are extreme. Our fundamental knowledge of how mechanical swarms act and react, whether in space or in the atmosphere, is also in nascent stages. Like the application of directed energy, microsatellite science and technology will continue to evolve for decades.

Perhaps none of the programs discussed in this paper faces greater challenges than JBI. This research is attempting to provide a framework for near-complete information sharing, by all levels of the Air Force and its partners, in a world that features many individual stovepipes. The research is further complicated by a world that not only has a continuous desire for more information, but one that is also constantly, and usually independently, producing more information. Even in a static, single-service environment, achieving the objectives of this program would be extremely difficult. Attempting to build a truly joint framework in the current organizational construct used by the Air Force (or the Army or Navy) is perhaps impossible. It is the most significant area in defense science and technology that would benefit from the strongest possible leadership, vision, and support from the Office of the Secretary of Defense, while simultaneously receiving similar and coordinated support from the Army, Air Force, Navy, and DARPA. Without this, neither the JBI nor other similar service programs will be realized.

Conclusion

The U.S. Air Force is unquestionably a service born of transformation that has continued this tradition into the present. Much of its attitude toward, and comfort with, transformation is a direct result of the close links that early Air Force leaders set in place between warfighters and their supporting scientists and engineers.

Air Force science and technology programs are unquestionably providing the basis for yet another wave of transformation. Although not without challenges, the new capabilities that unmanned combat aerial vehicles, small munitions, directed energy weapons, microsatellites, and joint battlespace infosphere bring to the Air Force are individually and collectively significant.

As it continues to reap the rewards of past investments in science and technology, the Air Force must make investing in its future a higher priority. In doing so, it should insist that more scientists and engineers give attention to reducing the cost of acquiring high technology. Senior Air Force leadership must also come to grips with its future in information science and technology. The lack of a truly joint activity here perhaps mirrors a similar situation in operational environments.

Although this paper has focused on science and technology programs, people are the heart of the many exciting technologies that currently exist and will arrive in the future. The Air Force has an excellent opportunity to shape this workforce over the next decade, and careful attention must be paid to hiring for the technologies of the future.

The words of General Hap Arnold, spoken nearly 6 decades ago, are just as true today: "The first essential of air power is preeminence in research."

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