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Senior Leader Perspectives

From the Editor

Features

The cyberspace environment presents conceptual and operational challenges for military leaders not unlike those associated with the early days of human flight. As technologies emerged to exploit each new domain, leaders at first dismissed them before finally recognizing the importance of dominance in the new environment. Although exploiting and defending cyberspace carries an opportunity cost, as early military leaders discovered with airpower, failing to properly organize, train, and equip for the new domain can undermine our current military advantage and our prospects for success.

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Tactical C4ISR and Conflicts—Past, Present, and Future

Thomas J. Rath

The Air Force's irregular warfare strategy calls for new approaches and synchronization of effort for the counterinsurgency (COIN) "long war"; however, this article contends that the Air Force's improvised airpower solutions for the unique COIN environment perpetuate mistakes of the past and jeopardize future successes in asymmetric conflict. The author echoes the call for a purpose-built command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) aircraft for the irregular warfare environment, which the Air Force can share with partner nations.

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Building on a Proper Foundation

Paul Smyth

Since the end of the Cold War, both the East and the West have engaged in protracted counterinsurgency (COIN) warfare. While historic COIN lessons remain obscure, advanced nations discover, to their frustration, that superior airpower employing conventional tactics can actually prolong conflict with a radicalized, recalcitrant enemy. The author explores limitations in the application of airpower, advocating an improved partnership between surface and air components to more effectively influence outcomes in irregular warfare.

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Right-Sizing Airpower Command and Control for the Afghanistan Counterinsurgency

Maj Gen Charles W. Lyon, USAF
Lt Col Andrew B. Stone, USAF

On 3 November 2010, the commander of United States Air Forces Central Command (COMUSAFCENT) signed and released an order establishing the 9th Air and Space Expeditionary Task Force–Afghanistan (9 AETF-A). This order represents an important moment because it alters the 20-year-old model of how COMUSAFCENT, in his role as the 9 AETF commander, presents forces to the supported joint force commander (JFC)—in this case, the commander of US Forces–Afghanistan (COMUSFOR-A).[1] This article serves as a complementary piece to Lt Gen Mike Hostage's article "A Seat at the Table," which appeared in the Winter 2010 issue of this journal.[2] It documents how this change in USAFCENT's airpower command and control (C2) structure developed, tempered by my observations and perspective as the commander charged with implementing the COMUSAFCENT's vision.

First, I explain the initial tasks that General Hostage gave me as director of the "empowered" air component coordination element (ACCE). As I do that, I illustrate how we began to evolve into what has become the AETF staff. Next, I discuss why this evolution was necessary and the rationale for creating a subtheater C2 echelon in today's war-fighting environment. I do so to give the readers of this journal one Airman's sight picture on how we can adapt centralized control procedures for a mature, enduring campaign. Finally, I offer a few thoughts on how and why we arrived at this juncture.

Empowered Air Component Coordination Element (2009–10)

I will cash any check my ACCE writes.

—Lt Gen Mike Hostage
COMUSAFCENT

The dialogue to empower the ACCE-Afghanistan (ACCE-A) organization began in earnest in 2009. My predecessor, Lt Gen (then Maj Gen) Stephen Mueller appealed for and received sufficient resources to place liaison officers across adjacent headquarters (HQ) structures in Kabul. This additional manpower ensured an Airman's presence in planning cells at Headquarters International Security Assistance Force (HQ ISAF), Headquarters ISAF Joint Command (HQ IJC), and Headquarters United States Forces–Afghanistan (HQ USFOR-A).[3] Simply stated, these Airmen "connected the wires" for cross-domain activities. General Hostage presented me his vision of the empowered ACCE construct when I first arrived in-theater in May 2010, saying, "Be all things Afghanistan." Initially, he gave me three tasks, later adding a significant fourth task. These four basic assignments set us on the evolutionary path from the empowered ACCE organization to the 9 AETF-A.

Task 1: "Support the commander of ISAF. . . . Help him succeed . . . by his measures of success."

In order to help the commander of ISAF (COMISAF) succeed, I first needed to know what he and his subordinate commanders considered important to the success of the population-centric counterinsurgency (COIN) campaign. I redoubled ACCE-A's efforts to understand the operational design of the campaign and to translate that design into measurable airpower objectives. The COMISAF's success does not hinge on the application of effects in the airpower domain (or in any single domain or mode). Rather, his success results from combined effects produced across three themes in the COIN operation: security, governance, and development. The COMISAF uses these themes to reach the military end state: creating a safe, secure environment sustainable by and for the Afghan people.

I shifted our organizational focus—people, processes, and products—to make sure we fully understand the commander's intent and keep the combined force air component commander (CFACC) informed. Does COMISAF particularly care how many sorties the CFACC generates in a day or the number of bombs his aircraft deliver? No. The commanders on the ground care about the ability of the air domain to shape and influence the situation on the ground. Instead of focusing on sorties/hours flown, we now measure the percentage of joint tactical air strike requests we fill per air tasking order (ATO) cycle and the average time it takes for an aircraft to respond to a troops-in-contact situation. We also measure our effectiveness rates for weapons employment. In other words, do we have aircraft in a position to support and enable ground operations in accordance with the COMISAF's priorities? Can we respond to an emergency for his troopers in a timely manner? Can we produce precision-weapons effects exactly where the ground commander asks for them? These are the questions we ask. Furthermore, the staffs of United States Central Command (CENTCOM), AFCENT, ISAF, IJC, and USFOR-A have vetted and agreed to the classified performance that we measure. The leaders responsible for succeeding on the ground have identified their "demand" signal, and we "supply" the assets to meet their objectives.

Task 2: "Execute Air Force forces duties and conduct planning activities."

Air Force Forces Duties. The US Air Force is "all in." Just over half of the US Air Force Airmen deployed to Afghanistan operate under the C2 of AFCENT. The remainder execute missions under the operational control of five other commands in Afghanistan—mostly led by commanders from the ground domain. These Airmen provide combat support and combat service support capabilities at the request of the JFC in Afghanistan—from individual augmentees at the four-star ISAF headquarters to joint expeditionary tasked explosive ordnance disposal teams protecting maneuver units at the battalion/squadron level. Nearly all troop-contributing nations in Afghanistan operate within force-management limits.[4] Our nation is no different. As the war evolves, the COMUSFOR-A reshapes his forces to adjust to conditions on the ground. The AETF commander now has responsibility for balancing risk across the task force to ensure that the right force structure is in place to meet campaign objectives. Arguably, the AETF-A commander functions as the "commander of Air Force forces–Afghanistan" (COMAFFOR-A) in this capacity. Regardless of the C2 relationships of the supporting Airmen, the AETF-A commander provides unique insight into the value of all US Air Force Airmen deployed to Afghanistan. As we seek to deploy more "trigger pullers" and off-ramp more "enablers," I now have the ability to prioritize the Airmen and the capabilities they provide relative to campaign objectives. This is an important contribution in my advisory role to the COMUSFOR-A.

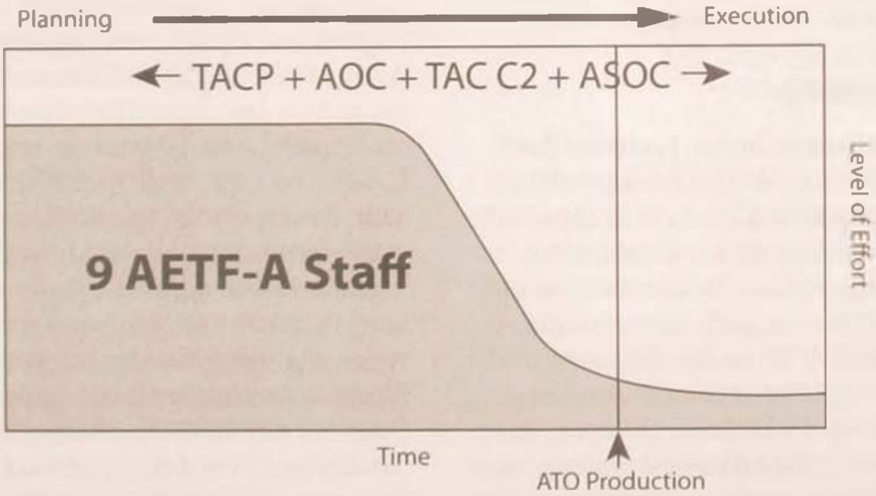
Planning. The COMUSAFCENT wanted a senior Airman with "boots on the ground" in Afghanistan to serve as the nexus for strategic and operational planning support to the COMISAF/COMUSFOR-A. I instructed my staff to be certain that they maintain a clear understanding of both strategic- and operational-level deliberate plans while maintaining awareness of regional command/division-level operations. The presence of liaison officers in key planning teams affords maximum opportunity to synchronize air component support to COIN operations. These officers request augmentation of subject-matter expertise from the combined air and space operations center (CAOC) or AFCENT/AFFOR staff, as needed.

We increased the air component's involvement in the other two pillars of the ISAF COIN strategy—governance and socioeconomic development—by infusing the expertise of Airmen into developing civil aviation infrastructure in partnership with US agencies and international partners. We work with members of the United States Embassy staff in Kabul to form an integrated civilian-military team that presents a unified approach to the Ministry of Transport/Civil Aviation as we jointly advise and assist ministry personnel in aviation issues. We also have increased our interaction with the NATO Air Training Command–Afghanistan to further leverage our Air Force's abilities to transform the Afghan Air Force into a professional partner.

Task 3: "The deputy CFACC remains responsible for execution—centralized C2 through the CAOC."

This task appropriately scoped the mission of the empowered ACCE—a reminder that the theater CFACC and the CAOC construct remain in place to conduct the details of building, distributing, and executing the daily ATO that services operations from the deserts of Iraq, across the Arabian Gulf, through the Hindu Kush in Afghanistan. The deputy CFACC continues daily execution of AFCENT air operations; this arrangement retains the proven centralized control model "as is" across the entire CENTCOM area of responsibility through the theater air control system (TACS). The 9 AETF-A staff concentrates on short- and midterm future plans, while the CAOC and TACS perform the ATO planning and daily execution tasks (fig. 1).

Beyond the execution role, the deputy CFACC is the ultimate arbiter of staff effort and priority as he weighs the multitude of tasks aimed at the CAOC and AFFOR staffs by himself, the CFACC, and both of the subordinate 9 AETF commanders (Afghanistan and Iraq). Again, Airmen understand centralized control—in the air and in the execution of staff duties. We established business rules



AOC = air and space operations center
ASOC = air support operations center
TAC = theater air control
TACP = tactical air control party

Figure 1. The 9 AETF-A's level of effort: planning versus execution over time

between the subordinate AETFs and the AFCENT staff. At first, "sharing" the staffs with subordinate AETF commanders presented a challenge, but the business rules resolved ambiguity and prioritization issues so that the various C2 nodes can function in harmony.

Air and Space Expeditionary Task Force (3 November 2010)

Liaison and coordination did not prove sufficient to satisfy the JFC.

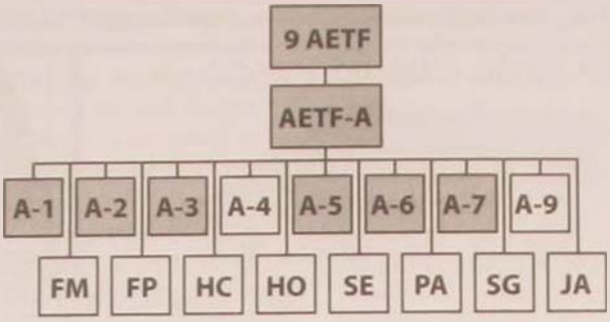
—Lt Gen Mike Hostage
COMUSAFCENT

Commanders have the unique authority to compel change in subordinate units. Inputs to a unit commander from anyone other than *his* commander are similar to suggestions from "a friendly uncle." General Hostage's vision of the empowered ACCE was clear—be all things Afghanistan. However, without the formal authorities and responsibilities of command, the empowered ACCE remained an adviser and a liaison—to the JFC and to air expeditionary wings alike. The order of 3 November 2010 establishing the 9 AETF-A formalized General Hostage's vision of an empowered ACCE and guaranteed it would transition to an enduring vision for Afghanistan.

Context for the Change

The current generation of Air Force senior leaders understands well the concept of the theater CFACC supported by a centralized C2 node embodied in the CAOC.[5] Our careers span the idea's emergence in the shadow of Operation Desert Storm and the subsequent maturation of the CAOC as the Falconer Weapon System. Air Force Doctrine Document (AFDD) 1, *Air Force Basic Doctrine*, includes the following foundational statement: "Centralized control and decentralized execution of air and space power are critical to effective employment of air and space power. Indeed, they are the fundamental organizing principles for air and space power, having been proven over decades of experience as the most effective and efficient means of employing air and space power."[6] That statement implies that the JFC is the geographic combatant commander (i.e., CDR USCENTCOM). Hence, it is easy to see why so few leaders have approached a subtheater AETF construct. However, after participating in and reflecting on two decades of continuous combat operations, some individuals find the construct of a single-theater CFACC without an intermediate command echelon an impediment to close coordination with our ground component partners in the COIN campaign—such as Afghanistan today. Some members of today's generation of Air Force senior leaders, myself included, recognize that a "one size fits all" approach to centralized C2 may not meet the needs of a protracted and complex COIN fight. A quick review of AFDD 1 reveals the pathway ahead: "The AETF is the organizational structure for deployed Air Force forces. The AETF presents a JFC with a task-organized, integrated package with the appropriate balance of force, sustainment, control, and force protection."[7]

The course of action we ultimately proposed and implemented for the 9 AETF-A structure mirrors the parent 9 AETF structure in many respects (fig. 2). I reorganized my staff to mirror an A-staff—by reengineering but not by increasing the staff size (i.e., manpower neutral). I am unwilling to off-ramp combat capability to bring in additional staff members. Therefore, we leverage the CAOC, AFFOR, and AFCENT staffs that provide the heavy lifting while our 9 AETF-A staff maintains close relationships with individuals in the adjacent staffs in Kabul. In fact, in recent iterations of force-management planning for the midterm, these Kabul-based adjacent staffs recognized the value that the AFCENT and larger US Air Force "reachback" model supplies. Consequently, they have begun establishing their own plans to relocate some of their support staff members outside Afghanistan to make headroom for additional combat forces within our national force-management limits.



Objectives:
- Manpower neutral - use existing ACCE-A manpower/expertise
- Reachback formalized - continue support relationship with AFFOR staffs at Shaw AFB, South Carolina, and Al Udeid Air Base, Qatar
- AETF-A chief of staff coordinates AFFOR staff taskings through adjacent chief of staff

▨ ACCE-A staff
☐ AFFOR direct support

A-1 = Personnel
A-2 = Intelligence
A-3 = Operations
A-4 = Logistics
A-5 = Plans
A-6 = Communications
A-7 = Mission Support
A-9 = Lessons Learned
FM = Financial Management
FP = Force Protection
HC = Chaplain
HO = Historian
SE = Safety
PA = Public Affairs
SG = Surgeon General
JA = Judge Advocate General

Figure 2. 9 AETF-A staff structure

Task 4: "When directed, be prepared to execute." (12 September 2010)

An additional task emerged as we were evolving into an AETF. The CFACC issued me the task to be prepared to accept tactical control of forces for limited periods of time. Should the theater CFACC lose connectivity across his area of responsibility for any number of reasons, the 9 AETF-A staff needs to prepare itself to serve as a short-term node in the AFCENT TACS. This is prudent planning in the cyber age and in a world of uncertainty. I assigned the staff tertiary responsibilities to assist the CAOC as required in the event we are pressed into service as the Afghan "execution" arm. As time allowed, we trained to meet minimum air and space operations center (AOC) "weapon system" qualifications through the tutelage of the 505th Command and Control Wing and the 609th AOC staffs. The wedge-shaped shaded area in figure 3 represents the requirement I see for 9 AETF-A to maintain working knowledge of and familiarity with daily operations in order to accept mission-type orders as a gap-filler for the TACS.

Final Thoughts

> *Effective integration at all levels requires more than close proximity. The ACCE needed, and I gave him, sufficient staff to integrate at all levels, responsibility for forces assigned to the joint operations area . . ., and the necessary authorities to respond to the JFC's needs.*
>
> —Lt Gen Mike Hostage
> COMUSAFCENT

Neither the formal structure nor my vision of the 9 AETF-A structure hatched overnight. The current form of the 9 AETF-A came about only through candid and open discussion from a variety of sources both from within my staff as well as outside it. The most important discussions were the one-on-one sessions with General Hostage. A fair amount of debate occurred over the need to formalize his intent. In the end, we all realized that Airmen understand and respond to the chain of command. The ACCE existed as a floating, unattached block on the AFCENT wiring diagram. The 9 AETF-A exists with clear lines of authorities and re-

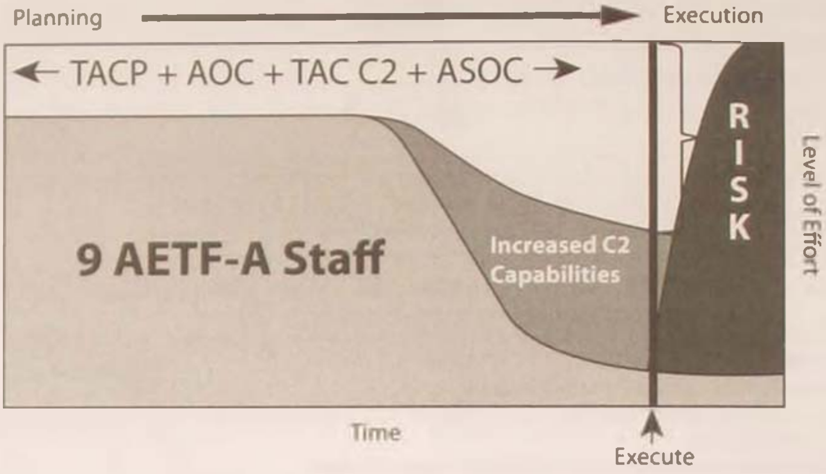


Figure 3. 9 AETF-A staff risk reduction

sponsibilities. The structure is in place and forms a repeatable mechanism for C2 in future personnel-rotation cycles.

The subtheater AETF (9 AETF-A, 9 AETF-Iraq [9 AETF-I]) tangibly improves the 9 AETF commander's support to the JFC by leveraging the capacity and capability to multitask the CAOC, AFFOR, and AFCENT staffs in support of the subordinate 9 AETF commanders (9 AETF-A, 9 AETF-I) while preserving the CFACC's flexibility to swing forces to meet emergent needs of the CDR USCENTCOM. This construct addresses historic concerns of Multi-National Corps–Iraq and COMUSFOR-A/COMISAF by presenting a task force commander rather than a senior liaison officer. The task force commander can shape his forces and operations support based on his detailed understanding of his respective JFC's ever-changing requirements through insight gained through daily interaction—in a dynamic and complex environment—while the CFACC/COMUSAFCENT focuses on supporting the CENTCOM commander's broader theater requirements.

In the coming years, as we continue to adapt our application of centralized control/decentralized execution across the full spectrum of military operations, we will find out whether this intermediate echelon of command is heretical, warranting the comments we heard about "Billy Mitchell rolling over in his grave," or whether it is a Billy Mitchell airpower success story. I have heard and embraced our Air Force's mantra *flexibility is the key to airpower* for over 30 years now. I believe the establishment of subtheater AETFs is just one example, implemented at the operational level of war, that shows the willingness of senior leaders engaged in the fight to sustain the flexibility of Airmen where it matters most—in combat. ✪

Notes

1. The commander of the International Security Assistance Force (COMISAF) is dual-hatted as the COMUSFOR-A. We refer to him as the COMISAF when discussing the overarching North Atlantic Treaty Organization (NATO) mission and specify him as COMUSFOR-A when discussing US-only issues.

2. Lt Gen Mike Hostage, "A Seat at the Table: Beyond the Air Component Coordination Element," *Air and Space Power Journal* 24, no. 4 (Winter 2010): 18–20, http://www.airpower.maxwell.af.mil/airchronicles/apj/apj10/win10/2010_4_05_hostage.pdf.

3. HQ ISAF is the four-star NATO strategic headquarters. Its mission is as follows: "In support of the Government of the Islamic Republic of Afghanistan, ISAF conducts operations in Afghanistan to reduce the capability and will of the insurgency." "About ISAF:

Mission," International Security Assistance Force–Afghanistan, http://www.isaf.nato.int/mission.html.

HQ IJC, the three-star NATO joint war-fighting command in Afghanistan, is one of several major subordinate commands to HQ ISAF. Established in November 2009, the command allows HQ ISAF to focus on "up and out" (strategic issues) while HQ IJC controls the "down and in" (operational fight).

HQ USFOR-A is the four-star US headquarters "intended to enable the most efficient command and control of U.S. forces in Afghanistan and ensure effective integration and coordination between U.S. and coalition forces operating under NATO/ISAF." "Defense Department Activates U.S. Forces–Afghanistan," news release, US Department of Defense, 6 October 2008, http://www.defense.gov/releases/release.aspx?releaseid=12267.

4. The term *force-management limits* refers to the US military troop-strength limit in Afghanistan established by the secretary of defense. The current limit calls for a maximum of 98,000 uniformed military personnel. The secretary has an additional 3,000 in reserve for emerging requirements, bringing the maximum number to 101,000.

5. I use the term *CFACC* for the purposes of this article, recognizing that some air component commanders may command joint, not combined, forces and that they are known as joint force air component commanders (JFACC). In parallel, the CFACC operates a CAOC, and not all air operations are "combined." *AOC* is the generic C2 term for the Falconer Weapon System.

6. Air Force Doctrine Document 1, *Air Force Basic Doctrine*, 17 November 2003, 28, http://www.e-publishing.af.mil/shared/media/epubs/AFDD1.pdf.

7. Ibid., 61. Combatant-commander-level presentation of an AETF is not a US Air Force canon.

Maj Gen Charles W. Lyon, USAF

Major General Lyon (BA, The Citadel; MPA, Golden Gate University; MS, National War College) is the commander, 9th Air and Space Expeditionary Task Force–Afghanistan and deputy commander–air, US Forces–Afghanistan. He oversees three air expeditionary air wings and three expeditionary groups consisting of more than 8,500 Airmen directly engaged in combat; he also advises and assists with joint expeditionary taskings / individual augmentee taskings in the Afghanistan combined joint operating area. Additionally, he serves as the personal representative of US Central Command's coalition force air component commander to the commander of Headquarters International Security Assistance Force (ISAF) as well as the deputy commander–air to the commander, US Forces–Afghanistan, thus ensuring the optimal integration of air and space power in support of Headquarters ISAF and Operation Enduring Freedom missions. General Lyon entered the Air Force in 1981 as a distinguished graduate of the Citadel's AFROTC program in Charleston, South Carolina. Prior to his current assignment, he served on the Air Staff as the deputy director, Directorate of Operational Capability Requirements. He has commanded a fighter squadron, an operations group, a fighter wing, and an air expeditionary wing in Southwest Asia. General Lyon is a command pilot with 3,800 flying hours, including more than 1,100 combat hours in Iraq, Afghanistan, and Serbia, flying the B-1B, F-16C, KC-135R, RC-135, E8-C, and RQ-1 remotely piloted aircraft.

Lt Col Andrew B. Stone, USAF

Lieutenant Colonel Stone (USAFA; MS, National Defense Intelligence College; MA, School of Advanced Military Studies) is chief of strategic plans for the 9th Air and Space Expeditionary Task Force–Afghanistan. Prior to his current assignment, he served as director of operations for the 6th Combat Training Squadron, Nellis AFB, Nevada. A senior pilot with over 1,800 flying hours, he has logged 360 hours of combat time in the A-10 in Operations Enduring Freedom and Southern Watch. Recipient of the Distinguished Flying Cross with Valor for Heroism, Lieutenant Colonel Stone is a graduate of Squadron Officer School, National Defense Intelligence College, the US Army's School of Advanced Military Studies, and the US Air Force Weapons School.

The Criticality of Defense-Focused Technical Education

Maj Gen Walter D. Givhan, USAF
with
Maj Eric D. Trias, PhD, USAF
Maj William H. Allen, USAF

The United States Air Force is a service born of technology, and throughout its history, technology has remained central to its identity and power. From the start, visionary leaders realized the importance of technologically focused education to advancing airpower. Consequently, through the years, institutions of higher learning such as the Air Force Institute of Technology (AFIT), as well as the civilian institution program it administers, have continued the meaningful work of developing the technology and organic human capital to sustain the Air Force's edge as a fighting force. As advances in technology have led the Air Force into the new domains and challenges of space and cyberspace, the role of delivering defense-oriented technical education has become even more critical. In this process, leveraging our network of science and technology partners to produce technically educated and operationally focused Airmen has proved as significant as the advances themselves. Because demand for these graduates continues to increase, deliberate investment in science, technology, engineering, and mathematics (STEM) education must also increase. Today, as yesterday, experienced Air Force leaders with a defense-focused technical education are essential to maintaining our military supremacy, and AFIT continues to meet that need—as it has since its inception in 1919.

In the Beginning

Even during the early days of aviation in Dayton with the Wright brothers—a time marked by fledgling, primitive technology (wood, wire, and fabric)—the miracle of powered flight inspired leaders to think of military applications and the transformational effect they could have. From that time to the present day, the education and research conducted at Wright-Patterson AFB, Ohio, have been instrumental in setting the course for the development of air, space, and cyberspace power. One of the visionary leaders present at the beginning, Col Thurman H. Bane, led the way in creating the Air School of Application, the forerunner of AFIT. Bane realized that technology lay at the core of the new Air Service's identity and capability; thus, technologically focused education for Airmen was central to the service's effectiveness. Bane wrote to the director of military aeronautics in Washington, DC, emphasizing the importance of education in support of the emerging airpower domain, observing that "no man can efficiently direct work about which he knows nothing."[1] The school's first class, led by Lt Edwin Aldrin (father of astronaut Edwin "Buzz" Aldrin Jr.), graduated in 1920. Since that time, AFIT has produced a string of senior leaders whose technical education and foundation have shaped the Air Force and its progress.

Two other airpower giants came to AFIT before they became legends. Future generals George Kenney and Jimmy Doolittle graduated in the classes of 1921 and 1923, respectively. Both went on to establish themselves as technical innovators as well as visionary leaders. Consider the relatively small investment made in the technical education of General Kenney between 1920 and 1921. The technical background he gained in school allowed him to push the known envelope of airpower as well as test new concepts such as mounting guns on the wings of aircraft and developing the tactic of skip bombing. The latter key innovation contributed to the total destruction of Japanese supply ships in the Battle of the Bismarck Sea.[2]

Doolittle's story also provides a classic illustration of innovation backed by strong technical education. A pioneer of instrument flying and the holder of multiple airspeed records, he consistently took calculated risks to advance the limits of flight. Doolittle graduated from AFIT with an aeronautical engineering degree in 1923 and from the Massachusetts Institute of Technology with a PhD in 1925. His famed raid on Tokyo in 1942 demonstrated both his leadership and his technical understanding of the requirements for doing something few people thought possible: launching B-25s from the deck of a carrier and hitting Japan before recovering to China.

Note another case in point: Gen Bernard A. Schriever, the "Father of the Air Force Space and Missile Program," whose story Neil Sheehan tells in his book *A Fiery Peace in a Cold War*, used his technical education in engineering from AFIT to lead the Air Force into the domain of space.[3] A shrewd and experienced leader who knew how to navigate the halls of Washington, he also understood the science and engineering required to engage with civilian scientists, engineers, contractors, and decision makers to shepherd the US intercontinental ballistic missile (ICBM) program from an idea to operational reality in a few short years. Schriever epitomized the scholar-leader who relies upon experience and education to lead in a dynamic environment and push the limits of the possible.

These individuals are but a few of the more prominent leaders who used their advanced technical education to achieve greatness. However, thousands of less well known graduates have made important contributions to developing the technology and science behind our ability to dominate each new mission area.

New Domains, New Challenges

As the Air Force mission expands, the breadth and depth of technical education requirements for our leaders continue to grow as well. Just as Schriever led the Air Force into space, so is a new generation of leaders pointing the way into cyberspace. This new war-fighting domain needs enormous amounts of STEM investment at all ranks and skill levels. Unlike air and space domains, the cost of entry to exploit cyberspace is low, yet the potential damage to the national security and economy is enormous. The complex cyberspace domain evolves at an astonishing pace.[4] Training is essential but not sufficient to ensure success. Therefore, we must also educate our force to anticipate, evaluate, and develop solutions to unforeseen problems in order to guarantee superiority in cyberspace. In response to the demands of Air Force Space Command, AFIT expanded its frontline role in educating these rising technical leaders by adding cyber professional continuing education to cyber graduate education and developmental education. This targeted, multitiered education delivers cyber-focused research projects and, more importantly, degree- or certificate-holding graduates who are technically prepared to move the Air Force into the cyber domain.

The Air Force continues to face difficult challenges as well as ever-growing pressure to become more efficient. One area of renewed focus stems from the Air Force's prioritization of its nuclear enterprise. Air Force Global Strike Command leads the charge but receives support from numerous entities that have an interest in the nuclear arena. The Secretary of Defense Task Force on Department of Defense (DOD) Nuclear Weapons Management singled out the underlying importance of education and training as key tools for generating a culture of nuclear excellence.[5] AFIT responded by revitalizing its nuclear engineering programs and offering certificate programs in addition to traditional graduate degrees with a revamped curriculum. It remains the sole source for defense-focused graduate degrees in nuclear engineering for both the Air Force and Army. Unlike civilian nuclear engineering programs that emphasize power generation or medical applications, those offered by AFIT address the essential task of solving unique defense problems. Besides safety and security of nuclear materials, the DOD has special requirements to study nuclear weapons' effects and their applications. Those demands drive the need for the corresponding defense-focused education and research readily available at AFIT.

Globalization, accompanied by reliance on resources, solutions, and human capital outside our borders, increasingly challenges our effort to maintain technical dominance. Technical innovation is at risk unless we continue to develop an indigenous pool of scientists and engineers from which the DOD and Air Force can draw to meet their needs.[6] Along with the Air Force Research Laboratory, AFIT serves as an organic source for STEM personnel and a place where the connection among applied research, education, and the mission is immediately apparent. In addition to their contributions as students, our graduates quickly find themselves in positions where they can put their advanced academic degrees to good use in service of Air Force and DOD priorities. The investments in their education have both immediate and long-lasting effects throughout their careers and beyond.

It Takes a Network

Keeping pace with technology requires a network of educators, researchers, and operational organizations that rely on technology to perform their missions. Active interactions among organizations that produce and need technical leadership supply the right leader at the right time in the right place. Leveraging partnerships and collaborations is essential to enhancing the educational experience and expanding research opportunities. AFIT is uniquely positioned at Wright-Patterson AFB to benefit from the proximity to its neighbors, all of them focused on science and technology: the Air Force Research Laboratory, Air Force Materiel Command, and National Air and Space Intelligence Center. Furthermore, AFIT partners with many institutions nationwide, such as the National Security Agency, Department of Homeland Security, and National Reconnaissance Office, to share expertise, laboratories, and resources for a common objective—advancing air, space, and cyberspace power for the Air Force and the United States. Long-standing partnerships among a multitude of defense, academic, and government stakeholders build an essential framework for delivering winning capability during times of war, changing missions, and fiscal uncertainty. The ultimate objective is to meet the war fighter's needs by ensuring that our graduates stay connected and attuned to current operations across the globe.

Natural career progression and the professional network inherent in the Air Force continue to create opportunities for partnering. Such partnerships are most critical and valuable when they respond to an immediate mission need. Through its connections to students' gaining and losing commands as well as its alumni, mission partners, and deployed faculty and staff, AFIT frequently becomes aware of urgent, developing requirements. In these cases, military organizations can respond with unmatched speed and flexibility without the need for complicated government-to-civilian contractual agreements. In 2009, when tasked by US Central Command to monitor the progression of the Afghan Air Force, NATO Training Mission–Afghanistan turned to AFIT for development of an automated tool kit that for the first time enabled the use of comprehensive data collection and regression routines to track key indicators. Within three months, AFIT had made available the first tool kit prototype. Also at the request of Central Command, AFIT is designing 22 logistics and acquisition courses for the Iraqi military, scheduled for delivery starting this year. AFIT possesses the invaluable organic capability to rapidly generate not only technical leaders but also science and technology innovations in a systematic way.

These kinds of examples show the value of a core technological education capability and of highly educated technical graduates in ensuring that the modern Air Force remains on the edge of innovation. Their research and classroom projects feed into war-fighting operations and research programs around the country. At the same time, state-of-the-art research reaches back to inform and refresh the classroom. This symbiotic relationship between research and curriculum requires a *critical mass* of students, faculty, and funding to thrive and generate the intended results. A robust technical program will produce capable technical leaders and show the way to potentially game-changing technology. Without a steady stream of defense-focused, technically educated individuals, every aspect of the technologically demanding Air Force mission will suffer. With graduates in such high demand, AFIT has transformed our educational methods by using Internet and satellite technology to bring itself to the Airman in addition to bringing the Airman to AFIT. These efforts produced 28,000 graduates of professional continuing education last year alone, in addition to 320 graduates with MS degrees, 31 with PhDs, and 2,600 from civilian institutions.

The Future

A recent report by the National Research Council of the National Academies identified the loss of technical competence within the Air Force as an underlying problem in several areas of science, engineering, and acquisitions.[7] At the same time, the *Report on Technology Horizons*, Headquarters US Air Force's vision for science and technology, recognizes that the capabilities we need also lie within the reach of potential adversaries because of their access to the same science and technology.[8] In the midst of budgetary constraints, advances in technology are imperative to increase manpower efficiencies as well as enhance the Air Force's capabilities. Several areas in which AFIT research and education directly support the *Report on Technology Horizons* vision include cyber resilience, adaptable autonomous systems, operating in an environment without benefit of the Global Positioning System (GPS), rapidly composable satellite systems, and improvement of space situational awareness. In the spirit of the *Report on Technology Horizons*, this edition of *Air and Space Power Journal* contains a small sampling of articles covering critical areas of research in cyberspace, energy and fuels, GPS alternatives, and technology that can improve wartime effectiveness and operational efficiencies.

As was the case with General Schriever and development of the ICBM force, these advances can occur efficiently and effectively only with the guidance and vision of leaders who have a solid grounding in science and technology that includes technologically focused education. Early on, Gen Henry "Hap" Arnold realized that scientists and engineers were the kind of people who would bring him the ideas he needed.[9] According to the *Air Force Science and Tech-*

nology Strategy, which serves as the cornerstone of all of the service's science and technology activities, maintaining our technological dominance faces a challenge from globalization and other nations' ready access to the technology and human capital that make possible the development of advanced capabilities. Furthermore, innovation is at risk unless the United States can develop scientists and engineers well grounded in STEM and attract them to careers in the Air Force.[10] AFIT serves as a key resource in meeting the need for well-qualified STEM professionals.

A defense-focused technical education can make no greater contribution than its graduates. These technically smart, savvy leaders are ready to tackle difficult problems. They make their presence felt even during their time as students conducting research relevant to today's problems as well as tomorrow's challenges. In the long term, their influence grows as their responsibilities increase, whether in the military or in industry. For example, AFIT's most recent distinguished alumnus, Dr. Ray O. Johnson, currently serves as senior vice president and chief technology officer for Lockheed Martin Corporation. His MS and PhD in electrical engineering from AFIT gave him the solid technical foundation he needed to succeed in the Air Force and, subsequently, in the defense industry. He is not alone, but we must produce more George Kenneys, Jimmy Doolittles, Bennie Schrievers, Lew Allens, and Ray Johnsons if we wish to maintain and sustain our technological edge as an Air Force and a country.

To this end, institutions must broaden their reach by increasing the diversity of sources for their STEM students. Although AFIT's primary student population consists of Air Force officers, military officers from all services attend, as well as those from many partner nations. Moreover, since 2004, 75 enlisted personnel have graduated from AFIT with MS degrees. These warrior-scholars have distinguished themselves in their studies and demonstrate once again how much we as an Air Force depend upon an educated and technically capable noncommissioned officer corps to succeed. Government civilians from the Wright-Patterson AFB community also attend AFIT, and within the last several years, the civilian student population has increased through sponsorship programs such as those of the National Science Foundation and the DOD's Science, Mathematics, and Research for Transformation (SMART) scholarships. The Dayton Area Graduate Studies Institute (DAGSI), another avenue for civilian students, emerged as a consortium among local graduate engineering schools to leverage resources and offer crosstown enrollments. Since DAGSI's inception, AFIT has graduated 119 STEM students out of the more than 700 DAGSI scholarship recipients; most of those students eventually secured government employment within the Wright-Patterson community.

One can make a strong argument that, despite these many efforts, we simply are not producing enough Air Force leaders with advanced STEM capability and degrees—in part because the current personnel model does not accurately reflect and manage the demand. Under discussion is a proposal to mitigate this problem by using an inventory management system, similar to the one used to manage the rated force. Such a system would capture the true demand and guarantee a sufficient pool of military leaders educated in defense-related technology.[11] It would also allow the limited number of technical PhD officers to expand their horizons and have more of an impact in operational and staff assignments, rather than find themselves rotating between faculty jobs at the Air Force Academy and AFIT because of the lack of other qualified officers available to fill those positions.

Back to 1919 . . . and Beyond!

Technology is part of Airmen's DNA. Our first leaders realized that fact even when the technology of flight was in its infancy. They also understood the importance of defense-focused technical education to carrying out our mission and to sustaining the Air Force our nation needs to attain its strategic goals. Advances in science and technology that have led us into new domains confirm the wisdom of that vision and the necessity of doing even more in this regard to preserve our edge and competitiveness.

When a corporation needs a new executive officer, it may promote from within or hire one with the desired experience from another organization. Military organizations, however, must grow their own. This pyramid of progression accentuates the necessity of investing in our Airmen to ensure that future leaders have the education and technical foundation to develop the capabilities demanded by our Air Force and country. At AFIT we prepare those leaders while advancing air, space, and cyberspace power for the nation, its partners, and our armed forces. We do so by offering relevant, defense-focused technical graduate and continuing education, research, and consultation. As Gen Charles A. Gabriel, former Air Force chief of staff, once said, "The AFIT of today is the Air Force of tomorrow."[12] That statement was true in 1919—and it's even truer today. ✪

Notes

1. Col Thurman H. Bane to the director of military aeronautics, Washington, DC, letter, 30 November 1918, in History, Air Force Institute of Technology: First Sixty Years, 1919–1979, 1-2.

2. Sam McGowan, "General George C. Kenney: Pioneer of Aerial Warfare Strategy and Tactics in World War II's Pacific Theater," *World War II* 11, no. 2 (July 1996): 10.

3. Neil Sheehan, *A Fiery Peace in a Cold War: Bernard Schriever and the Ultimate Weapon* (New York: Random House, 2009).

4. Office of the Chairman of the Joint Chiefs of Staff, *The National Military Strategy for Cyberspace Operations* (Washington, DC: Department of Defense, 11 December 2006), v, http://www.dod.gov/pubs/foi/ojcs/07-F-2105doc1.pdf.

5. Secretary of Defense Task Force on DOD Nuclear Weapons Management, *Report of the Secretary of Defense Task Force on DoD Nuclear Weapons Management: Phase I: The Air Force's Nuclear Mission* (Washington, DC: Department of Defense, September 2008), 4–5, http://www.defense.gov/pubs/phase_i_report_sept_10.pdf.

6. Office of the Chief of Staff of the Air Force, *Air Force Science and Technology Strategy, 2010* (Washington, DC: Office of the Chief of Staff of the Air Force, 2010).

7. National Research Council of the National Academies, *Examination of the U.S. Air Force's Science, Technology, Engineering, and Mathematics (STEM) Workforce Needs in the Future and Its Strategy to Meet Those Needs* (Washington, DC: National Academies Press, 2010), http://download.nap.edu/cart/deliver.cgi?&record_id=12718.

8. United States Air Force Chief Scientist (AF/ST), *Report on Technology Horizons: A Vision for Air Force Science and Technology during 2010–2030*, vol. 1, AF/ST-TR-10-01-PR (Washington, DC: Headquarters US Air Force, Office of the USAF Chief Scientist, 15 May 2010), http://www.aviationweek.com/media/pdf/Check6/USAF_Technology_Horizons_report.pdf.

9. Maj Dik A. Daso, *Architects of American Air Supremacy: Gen Hap Arnold and Dr. Theodore von Kármán* (Maxwell AFB, AL: Air University Press, September 1997), 119, https://research.maxwell.af.mil/papers/ay1997/books/Daso.pdf.

10. Office of the Chief of Staff of the Air Force, *Science and Technology Strategy*.

11. Lt Col Raymond W. Staats, Lt Col Marty Reynolds, and Maj Aaron D. Troxell, "Inventory Management of Officers with Advanced Academic Degrees: The Case for a New Approach," *Air and Space Power Journal* 21, no. 2 (Summer 2007): 42–52, http://www.airpower.au.af.mil/airchronicles/apj/apj07/sum07/sum07.pdf.

12. Gen Charles A. Gabriel (speech, AFIT Association of Graduates Banquet, Wright-Patterson AFB, OH, 15 December 1983), in History, Air Force Institute of Technology: First Sixty Years, 1919–1979, 7-2.

Maj Gen Walter D. Givhan, USAF

General Givhan (BA, University of the South; MS, Troy State University; MAAS, School of Advanced Air and Space Studies; MS, Industrial College of the Armed Forces) is commandant of the Air Force Institute of Technology (AFIT) at Wright-Patterson AFB, Ohio. AFIT's mission is to advance air, space, and cyberspace power for the nation, its partners, and our armed forces by providing relevant defense-focused technical graduate and continuing education, research, and consultation. A native of Safford, Alabama, General Givhan received his commission through Officer Training School. He served as the US air liaison officer to the commanding general, French ground forces, for Operations Desert Shield and Desert Storm. The general has commanded a combat training squadron, an operations group, an air base wing, and an air expeditionary wing. Prior to his AFIT assignment, he was the commanding general, Combined Air Power Transition Force, Combined Security Transition Command–Afghanistan, Kabul, Afghanistan. A command pilot with more than 2,500 flying hours in the T-37, T-38, T-1, AT-38, F-15, and A-10, he was a National Security Fellow at the Massachusetts Institute of Technology. General Givhan's military awards and decorations include the Legion of Merit with two oak leaf clusters and the Bronze Star.

Maj Eric D. Trias, USAF

Major Trias (BS, University of California–Davis; MS, Air Force Institute of Technology [AFIT]; PhD, University of New Mexico) is the director, Commandant's Action Group, and an assistant professor of computer science at AFIT, Wright-Patterson AFB, Ohio. He enlisted in 1988 and was a finalist for the Air Force Twelve Outstanding Airmen of the Year award in 1994. In 1998 he received his commission through the Airman's Education and Commissioning Program and Officer Training School. As a cyber operations officer, he has served operationally at Osan AB and Camp Humphreys Army Installation, Republic of Korea, and at the Distributed Mission Operations Center, Kirtland AFB, New Mexico. His research interests include knowledge discovery and data mining, information systems security, digital forensics, and various cyberspace-related topics. Major Trias is a graduate of Squadron Officer School and Air Command and Staff College.

Maj William H. Allen, USAF

Major Allen (BS, Christian Brothers University; MS, Air Force Institute of Technology [AFIT]) is the executive officer at AFIT, Wright-Patterson AFB, Ohio. He received his commission in 2000 through the University of Memphis ROTC program. As an engineer, he has served in several disciplines, including munitions test, rocket propulsion design, and evaluation and systems engineering. Major Allen is a graduate of the Aerospace Basic Course, Squadron Officer School, and Air Command and Staff College.

Air Force Institute of Technology in Focus; the Historic "Empowered" Air Component Coordination Element; and a Farewell to Maj Darren Stanford

Capt Wm. Howard, Editor

This quarter, *Air and Space Power Journal* (*ASPJ*) highlights the Air Force Institute of Technology (AFIT), at Wright-Patterson AFB, Ohio. Although the Air Force has many educational and research organizations, only AFIT can boast a heritage going back to the second decade of powered flight. Predating the renowned Air Corps Tactical School by a year, AFIT has helped develop thousands of astute airpower leaders and innovators throughout its history, contributing to the Air Force's global dominance in air, space, and cyberspace.

As the Air Force's source of advanced technological degrees, AFIT has educated students whose future creations ranged from instrument navigation systems for nighttime operations during World War II to intercontinental ballistic missiles during the Cold War. Since the institute's founding in 1919 as the Air School of Application and its redesignation as the Air Service Engineering School a year later, one would be hard pressed to identify an Air Force mission that has not benefited either directly or indirectly from AFIT's graduates.

To give *ASPJ* readers a current snapshot of student and faculty research, AFIT staff members solicited papers from a variety of disciplines for publication. Granted, the development of papers is a routine task at the graduate level, but the resulting studies can often prove exceedingly technical. Consequently, the delicate job of making scientific writing suitable for a general audience fell into the capable hands of Lt Col Stephen P. Chambal, PhD, director of AFIT's Center for Operational Analysis. With Colonel Chambal's assistance, students distilled complex research into accessible language, including actionable recommendations where appropriate. The *ASPJ* editorial board thanks him for facilitating publication of these scholarly papers.

Additionally, this issue of *ASPJ* features a second article detailing the successful transition to the "empowered" air component coordination element (ACCE). In the Winter 2010 edition, Lt Gen Mike Hostage, commander of United States Air Forces Central Command, discussed the rationale for vesting the ACCE with command authorities, thereby guaranteeing that airpower always had a "seat at the table" in joint operational planning. Complementing that article, Maj Gen Charles Lyon, ACCE-Afghanistan, writes about his historic command, further illuminating actual and anticipated improvements to the employment of airpower by joint force commanders supported by an empowered ACCE.

Finally, it is with deepest appreciation that *ASPJ* bids adieu to Maj Darren Stanford, deputy chief of professional journals, who is retiring from the Air Force. Major Stanford personally led *Journal* operations for three years, including one year as acting chief, maintaining the excellence of all six language versions of *ASPJ*. He superbly managed both the business operations and the rigorous editorial and peer review process, ensuring that vital air, space, and cyberspace power articles underwent proper scrutiny and refinement by editors and referees for worldwide publication. *ASPJ* thanks Major Stanford for his dedication to excellence—we are a better journal because of him. ✪

We encourage you to e-mail your comments to us at aspj@maxwell.af.mil. We reserve the right to edit your remarks.

FORTY-FIVE YEARS OF FRUSTRATION

Dr. Mark Clodfelter's article "Forty-Five Years of Frustration: America's Enduring Dilemma of Fighting Insurgents with Airpower" (Spring 2011) is a predictable academic article but misses the point entirely. Airpower is an essential element in counterinsurgency (COIN) strategy but not as a stand-alone solution. COIN strategy is a combination of combat operations, reconstruction, and nation building. The US/North Atlantic Treaty Organization (NATO) alliance flexes and adapts to the enemy's tactics each and every time he changes strategies. This has been the case from the Philippine Insurrection to the present time. Air operations against insurgents were effective in Vietnam (e.g., on the Ho Chi Minh Trail and in Linebacker I/II) as well as Iraq, and they are working quite well in Afghanistan. Many a combat veteran of these conflicts is alive today because air strikes and close air support broke up the enemy's formations before he could attack.

The problem with this article is that the issues Dr. Clodfelter highlights miss the mark. Although the high quality of his research is unmistakable, on page 82 he compares the sporadic bombing campaign against the Vietcong with the use of precision-guided munitions in Kandahar. Yes, there were unfortunate civilian casualties in both campaigns; however, careful application can reduce these numbers, as we have seen in recent US/NATO operations in Afghanistan. Film footage of North Vietnam before the cease-fire and the Peace of Paris showed a lunar landscape in a country teetering on the brink of collapse. Even today Vietnam has not recovered a viable economy in the south. Insurgents in these conflicts tend to cling close to the civilian population, both for support and for the propaganda advantage of "civilian casualties." Historically the insurgents themselves have always been responsible for the preponderance of civilian casualties, as clearly seen in Iraq and Afghanistan.

During the Vietnam War, the United States needed the political will to stay the course, as Pres. Richard M. Nixon clearly ascertained. We won the Vietnam War tactically but defaulted to the enemy when we left the playing field and pulled out. One must have the political will to stay the course. Many millions of people were left "holding the bag" when they were betrayed by this thoughtless nonsolution to that war's end. Dr. Clodfelter is quite correct in stating that "commanders—and their political leaders—must have a complete appreciation for the potential costs of such bombing" (p. 86).

Don't think for a minute that al-Qaeda and the Taliban are not currently reeling and bleeding from losses due to airpower. Anyone who asks an infantryman about close air support will sense that there is "no frustration here"—just gratitude that our airpower is there when we need it. God bless America, and God save our troops!

Gary Gault
Rosslyn, Virginia

FORTY-FIVE YEARS OF FRUSTRATION: THE AUTHOR REPLIES

I appreciate Mr. Gault's response to my article as well as the chance to respond to his comments; I had hoped that the piece might stimulate debate. I fully agree with him that airpower is not a "stand-alone" solution to solving the problems of COIN. The attempt by American political and military leaders to make it one in the initial stages of Rolling Thunder was a significant strategic error, given that the Vietnam War was primarily a guerrilla conflict waged by the Vietcong with limited assistance from the North in 1965. Airpower, if it is to be employed successfully, must suit the character of the war (that is, *who* fights and *why* they do so) as well as the conduct of the war (*how* war is fought). In COIN operations, it must also be applied in concert with other military elements, as well as diplomacy, information, and economics.

Pres. Lyndon Johnson's inability to achieve decisive success with any type of military force ultimately sapped not only the American public's will to fight but also his own desire to do so. The goal of a "stable, secure, independent, noncommunist Vietnam" was too amorphous to attain with airpower alone or in concert with ground forces, especially with a corrupt, out-of-touch government operating in Saigon. Johnson's successor pursued the goal of "peace with honor," but that objective was really a euphemism for getting American troops—and prisoners of war—out of Vietnam without having the South fall in the immediate aftermath of American withdrawal (in President Nixon's own words, the United States sought "a decent interval" for South Vietnam). During the North Vietnamese Army's Easter Offensive in 1972, airpower showed its value against an enemy that fought conventionally, and the two Linebacker campaigns helped to secure a negotiated settlement that secured the South two additional years of independence. Yet the character and conduct of the war fought in 1972 differed significantly from the insurgent struggle that occurred during most of the Johnson presidency.

In recent COIN conflicts like Afghanistan, precisely delivered airpower has certainly damaged the enemy's ability to operate effectively, and it has also provided effective close air support to engaged troops. Yet a relatively small number of aerial mistakes have often undermined bombing successes and served as recruiting mechanisms for an opposition adept at using information techniques, and for whom perceptions count far more than reality. As long as the United States pursues such open-ended objectives as "security" and "stability," airpower's ability to help secure them will remain problematic.

Dr. Mark Clodfelter
Washington, DC

THE MUTABLE NATURE OF WAR: THE AUTHOR REPLIES

I thank Col David Gurney and Col Jamie Sculerati ("Ricochets and Replies," Spring 2011) for their thoughtful comments on my article ("The Mutable Nature of War," Winter 2010). Naturally, I disagree with their arguments.

Colonel Gurney's first comment is that the initial objective of a planner is to accomplish the mission. Frankly, I thought that went without saying. Why else would a planner sit down to map out a strategy if not to fulfill the mission? OK, *then* the planner should do what I suggested in my article: he or she should attempt to perform that mission with the least cost in blood and treasure. If forces can carry out the mission without killing anyone on either side, then that would be preferable to, say, flooding a theater with hundreds of thousands of troops spoiling for a fight that may cost thousands of lives and billions of dollars. Regrettably, Colonel Gurney then follows with an inaccurate comment: that I am merely repeating "an enduring airpower fallacy"—namely, achieving results without great cost. The colonel must not have noted the examples I gave of Operations Desert Storm, Deliberate Force, Allied Force, Northern/Southern Watch, Enduring Freedom (when Kabul fell before the first conventional US ground troops ever arrived in the country), and, of course, Iraqi Freedom in 2003. Those aren't enduring fallacies; they are facts. Why shouldn't a planner attempt to replicate those wondrous campaigns?

Colonel Sculerati takes a different approach, but his reasoning is similarly incorrect. I argued that those who consider war the province of violence take their lead from Clausewitz. To the Prussian, war was battle and battle was *Schlacht* (slaughter). He is very clear on that point. He never mentions naval warfare; therefore, we cannot extend his argument by equating a naval blockade with slaughter, using the claim that violence *could* occur in the enforcement of a blockade or sanctions. In Haiti and Iraq, hundreds of thousands of civilians died, quietly and alone. There was no violence—none. But even if one accepts Colonel Sculerati's argument that a ship or two attempted to run the blockade and took fire (the violence he imagines), it would not change the basic condition: Clausewitz and his ilk specifically write of slaughter and violence on the battlefield. That is not at all the same as a blockade, which seeks to kill or starve civilians—and has done so for centuries. If violence occurs at sea due to a blockade runner, it is incidental to the intent of the blockade—to kill the women, the children, the old, and the sick located within a country under siege. Surely Colonel Sculerati must see the difference between the cause and effect of a Clausewitzian battle/slaughter and that of a quiet 13-year blockade of Iraq. As far as I know, the latter entailed no violence whatsoever yet killed over one million civilian noncombatants.

Colonel Sculerati's second point actually refers to a different part of my argument—the Clausewitzian notion, repeated by numerous contemporary commanders, that war is the province of danger, fear, thirst, pain, physical exertion, and hardship. Consequently, we hear that war for grunts in Afghanistan today differs little from the one for Alexander's hoplites. This is the "enduring nature of war" argument made by people like Lt Gen Paul Van Riper. I use the examples of drones and air warfare in general (as well as cyber war) to show that oftentimes no sense of danger, fear, thirst, pain, physical exertion, or hardship accompanies those types of war—the ones featuring a Reaper flown from a hangar in Nevada. Soldiers or Marines who can still pretend that war's nature is timeless willfully ignore modern air warfare, which, I argue, differs fundamentally from what they claim warfare is "really all about."

Col Phillip S. Meilinger, USAF, Retired
West Chicago, Illinois

GLOBAL POWER: THE AUTHOR REPLIES

Regarding my article "Global Power Requires a Global, Persistent Air-to-Air Capability" (Winter 2010), Lt Col Paul Matier ("Ricochets and Replies," Spring 2011) points out some problems with arming B-1s with advanced medium-range air-to-air missiles (AMRAAM) that I generally agree with. That said, the point of proposing the B-1 option is that it is the fastest way to get a minimal capability in service and is the cheapest possibility. It is anything but a panacea.

In several earlier (much longer) drafts of my article, I specifically stated that a simple AMRAAM-armed B-1 (even several) would not be capable of going up against a near-peer adversary, as in a Taiwan Strait or Baltic scenario. An air-to-air capability much more robust than a couple of AMRAAM-armed B-1s would clearly be required.

Having been closely involved in the recent Libya issue, though, I believe that it is the perfect scenario for my proposal. In Libya, air-to-air armed B-1s really could have rapidly dominated a foreign air force (arguably much more rapidly than our governmental and command and control processes can react) without any concern about foreign basing rights and ponderous logistics processes.

Additionally, in the Taiwan Strait, there is also no real doubt about the outcome of an engagement between a handful of Chinese aircraft and an Aegis cruiser with lots of missiles. The main difference is that the B-1 might have the option of "running away" while the Aegis cruiser would not; its only option would involve finding itself on the bottom of the ocean. That, however, does not prevent us from buying plenty of Aegis cruisers/destroyers (and aircraft carriers, for that matter).

Fundamentally, this is one problem with the Air Force mind-set. We tend to dismiss possibilities that are not viable against a near-peer adversary as not worth spending money on. Yet, the Marine Corps and our other sister services spend amazing amounts of money on systems and capabilities that are not viable against near-peer adversaries. The Marine Corps itself is a combined-arms service capable of going one-on-one with most of the militaries of most of the nations of the world, almost by itself. Clearly, it is not able to do that against a near-peer adversary, and many of its capabilities are of questionable value in any conflict with a near-peer adversary.

Lt Col Bruce D. Cox, USAF
Ramstein AB, Germany

CIVILIAN LANGUAGE EDUCATION IN AMERICA

The US military has become the strongest armed force in the world, partially by harnessing perceived internal crises in order to keep evolving. When it comes to the reserve of linguistic talent, Col John Conway's article "Civilian Language Education in America" (*ASPJ*, Fall 2010; *ASPJ in Chinese*, Winter 2010) clearly demonstrates how the US military is capable of identifying its own strategic shortcomings and being open enough to discuss remedies. Many Chinese readers perceive Americans as complacent in terms of language skills—the stereotype is that they generally do not bother to learn a second language. In contrast, Chinese students begin foreign language study at a very young age. By the time a student leaves college, he or she has earned a level-four English certificate. [Editor's note: This level of proficiency would satisfy most American universities' admission requirements for international students.] Thus, it appears that the average Chinese citizen (not just those in uniform) seemingly has far more advanced language skills than his or her US counterpart. This perception is wrong; therefore, I recommend that those who have this impression read Colonel Conway's article.

Yes, almost everyone in China learns English. Although important, English is only one language, and there are a host of other languages that Chinese students could be studying. Unfortunately, China places little emphasis on teaching such languages. Colonel Conway indicates that in 2006, a total of 7,145 (US) students enrolled for Korean language instruction; the numbers are much higher for the other "less commonly taught languages" (table 2, p. 80). By comparison, China has far fewer individuals enrolled in non-English-language courses in both civilian colleges and the military.

Colonel Conway's article also mentions that the US Air Force offers no Air Force specialty codes for linguists and does not require foreign language qualifications for commissioning (p. 79). But it is my understanding that the United States is a nation of immigrants. Many US families (including military members) naturally speak English as well as their "mother tongue." Many of them are bilingual, with or without a language learned in school. It is only because the United States is pursuing global supremacy, which requires global military presence, that the US military has begun to feel the urgency for a talent reserve in less-used languages—hence, the "wake-up" call by Colonel Conway. When I look at the language map, few of China's neighboring countries use English; most of them speak the so-called less commonly taught languages. From a strategic point of view, if the US military has identified language skills as a serious deficiency, then the situation is much worse within the People's Liberation Army.

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Precision Position, Navigation, and Timing without the Global Positioning System

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Dr. John F. Raquet*

The NAVSTAR Global Positioning System (GPS) has revolutionized modern warfare. Since 2005 almost all US precision-guided munitions have used GPS targeting data.[1] Consequently, weapons delivery systems are able to strike enemy targets with precision, often resulting in little or no collateral damage. Furthermore, nearly all military assets, including aircraft, tanks, ships, missiles, mortar rounds, cargo boxes, and dismounted Soldiers rely on the accurate position determination that GPS provides.

For military users of this system, two main limitations emerge. First, the system relies on line of sight—that is, the satellites must be in "view" of the receiver's antenna so that it can acquire the signals. This limitation is most pronounced indoors (including underground) and in urban areas, presenting significant navigational challenges for ground forces, remotely piloted aircraft, and precision munitions. Tall buildings in urban areas block satellites from view and create reflected or "multipath" signals, confusing GPS receivers. Indoors, GPS signals are present but greatly attenuated; as a result, ground forces operating under protective cover have difficulty obtaining a reliable GPS position.

Second, adversaries can easily defeat the system's signals by using simple techniques and readily available equipment. "Jamming" results when adversaries emit signals that interfere with the relatively low-powered GPS signals. Reportedly, China has deployed GPS jammers in a fleet of vans, and several Internet sites even offer small, inexpensive devices to counter GPS-based vehicle tracking.[2]

Finally, a severer yet far less likely denial scenario involves other nations using antisatellite technology to disable or destroy one or more satellites in the GPS constellation. Three nations already possess such technology: the United States, Russia, and China, which demonstrated an antisatellite capability with a surprising attack on one of its own aging weather satellites in 2007.[3]

Regardless of the reason, when GPS capabilities become degraded or unavailable, the military needs a navigation alternative that offers comparable accuracy and utility. Researchers in the Advanced Navigation Technology (ANT) Center at the Air Force Institute of Technology (AFIT) are working to provide GPS-like accuracy without the use of GPS. The ANT Center is investigating methods to calculate position by using radio beacons, man-made and naturally occurring signals of opportunity (SoOP) (including magnetic fields), and vision aiding. In the future, a robust alternative to GPS will

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likely employ a combination of these techniques. A review of basic navigation concepts will help place these non-GPS approaches in perspective.

Navigation: An Overview

What Is Navigation?

In early history, mankind was predominantly interested in localized navigation, which entails determining a position in the vicinity of a local living area. People did so mostly by identifying landmarks and using their known locations to determine position. Later, especially when ship travel greatly expanded mobility, travelers needed a means of global navigation.[4] Early sailors navigated by keeping track of the direction and distance traveled on each leg of a voyage, a technique known as *dead reckoning*.[5] Even though navigation has improved dramatically, many modern systems (such as an inertial navigation system [INS]) are still based on dead reckoning (from the perspective of starting from an assumed position and tracking changes in position, speed, direction, and/or distance over time).

Navigation Trends

Though modern INS can be quite accurate over short periods of time, precise navigation and coordination over vast regions require extremely rigorous positional information—thus the need for GPS technology. GPS has become the cornerstone of modern navigation, and improvements in its technology over the past 20–30 years offer system users the ability not only to navigate precisely to within feet or even inches of the intended destination, but also to synchronize operational systems and equipment for unprecedented efficiency. For military users, these efficiencies translate into operational advantage through economy of force, mass, and the element of surprise. The Department of Defense and commercial industry increasingly use systems in which multiple, interdependent vehicles work together to attain a goal or mission (often automatically)—an objective that almost always requires reliable navigation. In fact, a number of systems need GPS in order to operate (not just navigate), taking for granted the system's availability. Furthermore, improvements in GPS accuracy (in both equipment and the algorithms that support it, such as differential GPS) can remove most of the errors found in its signals. Now, users can routinely obtain near-centimeter-level positioning accuracy for certain applications such as precision landing and, in the future, automated aerial refueling of military aircraft. As the pool of potential "customers" of GPS technology grows, the market is responding with lower-cost, smaller receivers to satisfy demand. The ubiquity of GPS has increased the inclination of users (especially those in the military) to track everything—every Airman or Soldier engaged in combat operations, every piece of airfield equipment, every vehicle, and so forth. In the past, we were content to track only major items of equipment such as aircraft because of the size and expense of traditional navigation devices and early GPS receivers. Today, literally every Soldier can have a GPS receiver in his or her rucksack.

As military and commercial reliance on GPS increases, so does vulnerability to interruption or defeat of the system. Therefore, users need equipment with backup navigational and synchronizing capability for situations in which GPS does not work. The chief scientist of the Air Force recently identified "PNT [position, navigation, and timing] in GPS-denied environments" as one of the top 12 (in terms of priority) research areas that we should emphasize in the near future.[6] Researchers at the ANT Center focus on exactly this problem by considering navigation approaches that do not rely upon GPS.

Since the system does offer accurate PNT in most situations, a suitable alternative usually demands combining two or more sensors using a navigation algorithm. The remainder of this article explains the general concepts underlying navigation algorithms and sensor integration and then describes four different non-GPS navigation techniques under research at the ANT Center.

Navigation Algorithms and Sensor Integration

A navigation algorithm blends information, conveniently expressed through a *predict-observe-compare* cycle (fig. 1). "Navigation State" at the lower right of the figure represents the user's current navigation state or all of the information about the user's position, velocity, and so forth, as well as estimates of that information's quality. One can think of this state as the system's best guess of the user's position and the system's estimation of the accuracy of that guess. As depicted in the "Sensor" box, the system measures or observes data that gives it some insight into the user's navigation state. For GPS, the system observes the range to a satellite. It also uses a model of the real world, depicted as the "World Model" box. In the case of GPS, this model might consist of the locations (orbits) of the GPS satellites.

During the *predict* phase, the system uses the world model and the navigation state to predict what the system expects to observe; the "Prediction Algorithm" box in the figure depicts this process. During the *observe* phase, the system receives a noise-corrupted measurement from the real world. During the *compare* phase, the algorithm matches the predicted measurement to the actual measurement and uses discrepancies to improve the navigation state and possibly the model of the world.

Consider the following simplistic navigation example: a user attempts to determine his position from a wall. Using his eyesight to judge the distance, he *predicts* that it is about 30 feet. (At this point, the navigation state is 30 feet with high uncertainty.) The user then measures or *observes* the distance as 31.2 feet, based upon the calculation of a precise laser range finder. Next, he *compares* the prediction to the observation, quickly dismissing the former and trusting the latter because the user trusts the laser-based observation much more than the current navigation state (which was based upon eyesight).

The most interesting applications blend prediction with observation, a condition that arises when a comparable degree of trust exists in both the prediction and observation even though they disagree. To handle this blending, typical INS/GPS applications use a Kalman filter to perform the predict-

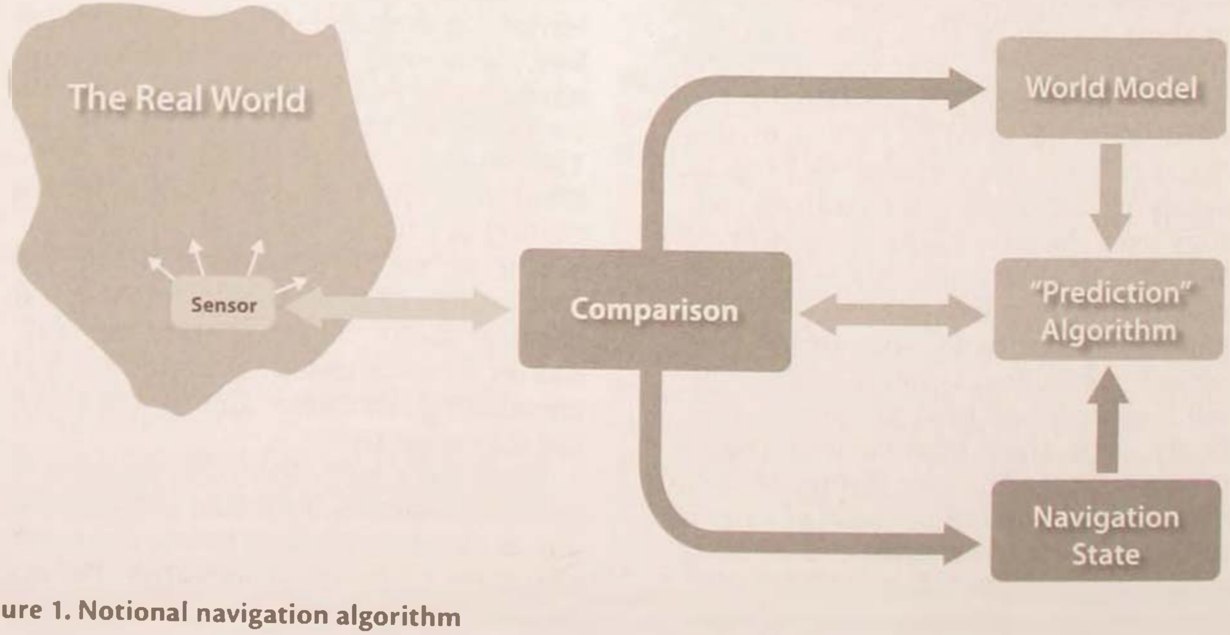

Figure 1. Notional navigation algorithm

observe-compare cycle.[7] The INS predicts the user's position by keeping track of his or her movements, and then the GPS receiver "observes" the user's position by using measurements from the system's satellites. Finally, a Kalman filter compares the INS prediction to the GPS observation, generating a blended solution based upon the relative quality of the two results.

Typical modern navigation systems blend an INS with GPS updates to produce a robust navigation estimate—"robust" because the dual inputs complement each other. The INS provides a nearly continuous, accurate estimate of vehicle motion but accumulates errors over time. For example, even the most precise INS initialized very close to the true position will eventually amass errors that render its position estimate unusable. Conversely, GPS updates occur less frequently, but errors do not accumulate. Used in tandem, the INS supplies an accurate navigation estimate over the short term while GPS provides an accurate solution over the longer term. In other words, the GPS sensor constrains the drift of INS errors.

Four Promising Navigation Techniques for Position, Navigation, and Timing in GPS-Denied Environments

Navigation Using Beacons

Beacons (i.e., sources of man-made signals broadcast for navigational purposes that augment or replace GPS signals) can counteract the effects of intentional interference or weak signal environments. The Defense Advanced Research Projects Agency (DARPA) instituted a program to "demonstrate the use of airborne pseudolites, which are high-power, GPS-like transmitters on aircraft, to broadcast a powerful replacement GPS signal that 'burns through' jammers and restores GPS navigation over a theater of operations."[8] Actual field demonstrations showed that airborne pseudolites could replace satellite broadcasts, providing good-quality navigation signals to military GPS receivers with only software modifications to the receivers.

Other researchers use beacons to transmit unique signals that require receivers specifically designed to navigate, based upon those signals. One company uses terrestrial beacons placed in a local area to assist GPS or to navigate without that system.[9] One can even use these beacons to locate someone's position within a subterranean mining complex; moreover, they might prove useful to ground troops operating in enclosed locations. From an operational viewpoint, this approach necessitates fielding transmitters from either ground sites or airborne platforms.

Navigation Using Man-Made Signals of Opportunity

GPS navigates by tracking signals transmitted from satellites. Navigation that uses SoOPs builds upon this concept, except that SoOP navigation tracks signals transmitted for purposes other than navigation (e.g., AM and FM radio, satellite radio, television, cellular phone transmissions, wireless computer networks, and numerous satellite signals). ANT Center researchers have explored television signals, AM radio signals, digital audio/video broadcasts, and wireless networks.[10] Given the wide variety of SoOPs available, researchers developed a mathematical tool to determine such a signal's usefulness for navigation.[11]

SoOP navigation enjoys several advantages over GPS. First, SoOPs are abundant, ensuring the availability of sufficient signals for position determination and for reducing position error. Second, SoOPs are often received at higher signal strength than GPS signals.[12] (Unlike GPS signals, those from FM radio stations or cellular phones are often available and usable indoors.) Finally, the navigational user incurs no deployment costs or operating expenses related to the SoOPs. (Of course, mobile receivers, akin to

GPS receivers, would require design and fabrication to field such a system.)

Using SoOPs for navigation purposes does have disadvantages, however. Because the system did not intend that these signals be used for navigation, their timing is neither necessarily linked nor synchronized. Additionally, the navigation user may not know exactly what was transmitted. To alleviate these two issues, typical SoOP navigation scenarios employ a base station—a receiver at a known location within the vicinity of the user's receiver. The base station enables the latter device to extract features from the SoOP, making the timing issues less severe. Most algorithms also assume that the SoOP transmitter (e.g., the radio station tower or wireless router) occupies a known location although methods exist for determining this information. Multipath or reflected signals—predominant error sources in SoOP navigation—often prove difficult to eliminate.

Orthogonal frequency-division multiplexing represents a particularly promising SoOP signal structure used for digital audio/video broadcasts and many wireless network devices. These signals exhibit navigation benefits not found in others, such as redundant information interwoven within the signals, from which a user may obtain navigation data by eavesdropping (i.e., passively listening to a signal) without using a base station.[13] Closely related research includes attempts to use radio-frequency fingerprinting to associate each signal with a particular transmitter.[14]

There are also SoOP navigation methods other than the ones that use timing information obtained from tracking a SoOP (akin to GPS navigation). For example, we can make use of angle-of-arrival data (typically found using multiple antennas) for navigation by bisecting multiple arrival angles to determine the receiver's position by triangulation. Additionally, we can utilize a SoOP's received signal strength (RSS) to estimate the range to a particular transmitter. A commercial vendor even offers a database of wireless network locations and transmitted power for use in RSS calculations.[15]

Navigation Using Naturally Occurring Signals of Opportunity

Although man-made SoOPs represent a rich field of study, naturally occurring SoOPs are also available. Fundamentally, any source that allows someone to distinguish one position on Earth from another is suitable for navigation. A phenomenon's usefulness for positioning often depends upon how reliably we can measure it; how well the measurement corresponds to a user's position; and the size, weight, and power of the sensor. Numerous naturally occurring SoOPs are potentially suitable for navigation, including magnetic fields, gravitational fields, and lightning strikes; however, navigation based on magnetic fields remains the most promising for military applications.

We find magnetic fields (in varying intensities) everywhere on Earth. In addition to Earth's main magnetic field, other such fields occur in any conductive material (such as rebar, wall studs made of steel, pipes, wiring, etc.). Thus, the magnetic field intensity at a specific point in a particular hallway in a particular building is unique. Researchers at the ANT Center have tested the feasibility of using such intensities to aid navigation systems indoors by first comparing measurements from a small magnetometer (about the size of a deck of cards) to a previously determined magnetic field map of the indoor area.[16] Then, they determined the user's position by finding the location on the map having the highest correlation with the magnetometer measurement. Although the results proved quite promising, a couple of areas require more research. First, the system relied upon a previously determined magnetic field map. Because we cannot realistically expect war fighters to survey an area, research is under way to build a magnetic field map as they move. Second, researchers are exploring variations in magnetic fields over time and the resistance of the magnetic field navigation algorithm to large deviations in the observed field (which may occur with the addition or removal of metal objects from the scene).

Vision-Aided Navigation

Vision-aided navigation uses cameras to produce an alternative and highly complementary system for constraining inertial drift. Instead of directly computing the location of the vehicle, vision systems use the perceived motion from image sensors to aid the INS. For example, suppose a person rotates as he or she sits in a chair. Physiologically, the vestibular system senses the rotation; however, eyesight can aid in the rotation estimate by observing the motion of visual cues. In a similar fashion, vision sensors can aid an INS and thereby improve navigation.

Other than improved navigation performance, several advantages accompany vision-aided navigation systems. First, computer vision techniques are immune to attacks that disable GPS (although vision-based tools do have their own limitations, such as those imposed by fog or smoke). Second, as cameras and computers become more capable and less expensive, computer vision is quickly becoming a realizable and cost-effective solution. Third, a camera used for navigation can also gather intelligence. Similarly, a camera used for intelligence gathering may also lend itself to navigation. Furthermore, we can integrate data with mapping information from the National Geospatial-Intelligence Agency or commercial imagery providers such as Google Maps.

Due to computing complexity, typical vision-aiding algorithms employ features selected from an image rather than the entire image. The algorithm matches features between successive images to estimate the relative motion of the platform. The quality of feature matching depends upon the characterization and identification of the features in subsequent images. We can further reduce computational complexity by limiting the analysis to a small portion of an image. These computational improvements allow us to utilize vision systems on relatively small platforms. ANT Center researchers have combined a faster but less robust feature-tracking algorithm with a commercial-grade INS to attain real-time performance on a small indoor remotely piloted aircraft.[17]

The distance from the camera to a feature (i.e., depth perception) represents a key aspect of image-aided navigation. ANT Center researchers have mimicked human eyesight by using two cameras for stereo, image-aided navigation and have demonstrated their algorithms in near real time.[18] Unfortunately, this method relies on physical separation between the cameras, so we cannot readily employ it in miniaturized applications (e.g., on board a micro aerial vehicle).

Augmenting a single camera with a small, gimbaled laser range sensor avoids the physical requirements of stereo vision systems. The ANT Center has used such a sensor to measure the depth to any near object within a camera's field of view.[19] These sensors, along with an inertial sensor, can help navigate a micro aerial vehicle without the use of GPS—an ideal setup for indoor exploration and mapping missions. In addition to providing a non-GPS navigation solution, this small, lightweight sensor combination can locate and image objects or targets for use in intelligence or targeting applications.

Unlike selecting features, predictive rendering—another area of active research in vision-aided navigation—uses knowledge about an object to estimate a platform's motion. Researchers at the ANT Center are applying this method to air-refueling scenarios. Specifically, a three-dimensional model of the tanker aircraft permits computers to predict an image of the aircraft from the perspective of the receiver platform. After cameras capture an actual image, an algorithm compares the predicted to the observed image. This navigation scheme uses image-processing techniques that simplify the correlation between predicted and true images (i.e., the extent to which the two images match).[20]

Combining a Communications/Navigation Device with a Vision-Aided Inertial Navigation System

One promising concept may give the war fighter an integrated handheld device for communications and navigation. Dismounted Soldiers frequently carry both a handheld radio and a GPS receiver. Combining these devices into one unit would allow those Soldiers to use the communications link between the radios to make positioning less reliant upon GPS. Furthermore, an onboard vision-aided INS offers short-term stability and attitude information. Just as a GPS-aided INS combines the long-term stability of GPS solutions with the short-term stability of an INS, so may the proposed integrated device have potential for relatively long-term, precise non-GPS navigation.

Researchers at the ANT Center and Raytheon Corporation are using ranging measurements based upon a Raytheon DH-500 handheld communication device to determine the user's position without resorting to GPS.[21] This packet radio system features ranging capability in addition to robust communication. Recently, the ANT Center combined Raytheon DH-500 radio-ranging measurements with a stereo vision-aided INS for precise non-GPS navigation.[22]

This type of research serves as the gateway to a broader class of problems—namely, using combined navigation/communications handheld devices augmented with other sensors to navigate and communicate synergistically. These devices may also permit multiple platforms to cooperate within a network, offering even more information from which to navigate.

One Size Does Not Fit All

For the vast majority of military applications, GPS (or GPS with INS) meets navigation performance requirements when it is available. If the system is not available, we must fall back on alternative navigation approaches like those described above. However, compared with GPS, all of the latter have significant drawbacks. For example, beacon-based navigation does not apply worldwide and requires deployment of beacons. Navigation using SoOPs must have access to the right kinds of signals (it is also susceptible to all of the other downsides described previously). Vision-based navigation does not work well in fog or over the ocean. Radio-ranging-based navigation works only in the context of multiple vehicles. Consequently, no single approach would serve well as an alternative to GPS in all environments. Research that develops our ability to navigate using non-GPS signals is important and should continue. However, simply having more options does not offer a complete answer.

The Way Ahead: All-Source Navigation

The Air Force must embrace an all-source navigation approach to solve precision navigation without GPS.[23] An all-source navigation algorithm computes a precise solution from the platform dynamics, using all available information. Figure 2 depicts a notional scenario that relies upon an INS and uses the following additional sensor information: GPS, SoOPs, vision, light detecting and ranging, magnetic fields, gravity, and radar. Note the intentional inclusion of GPS (an all-source navigation system should use that system when it is available). Thus, the system combines all available information and employs a reduced sensor subset when some sensors are not accessible.

The ANT Center is developing systems that can easily adapt to specific situations by using the most appropriate sensors. For example, image-based navigation may prove suitable for an urban environment in daytime, whereas a less accurate gravity-field-based approach may be the most appropriate for en route navigation over the ocean. Clearly, different situations call for different sensor suites. Problematically, however, current integration architectures generally do

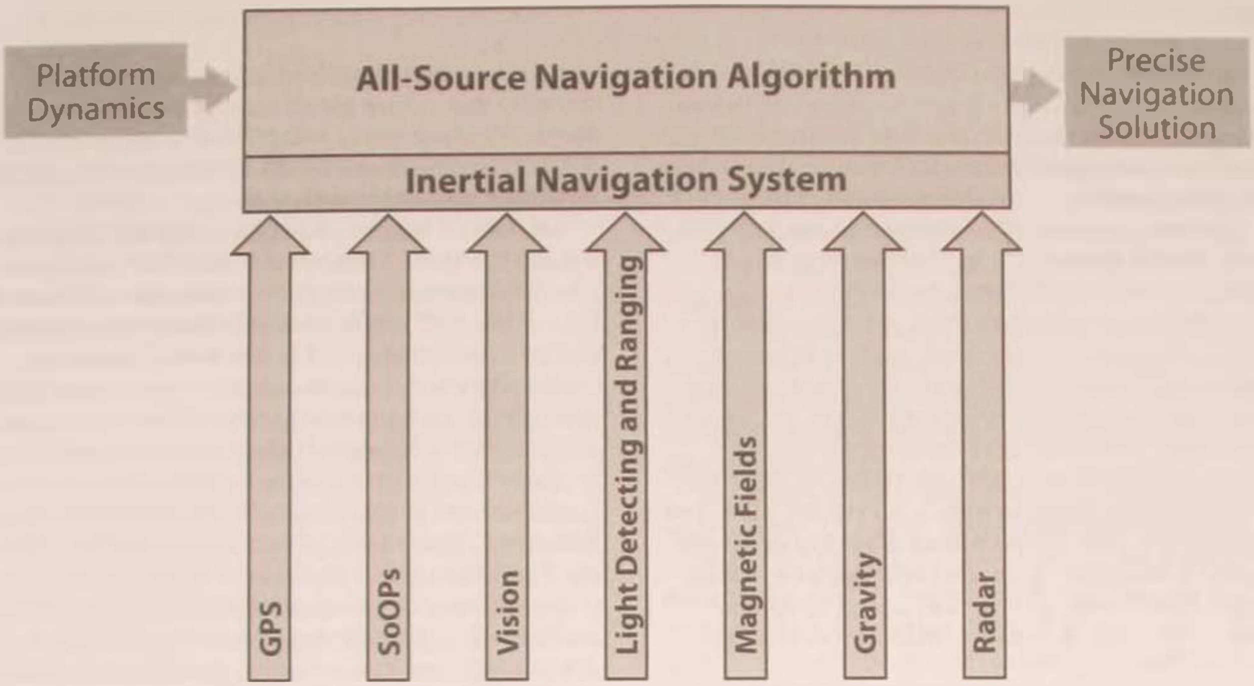

Figure 2. Notional all-source navigation algorithm

not allow for easy swapping of navigation sensors. Because most integrated navigation systems are custom designed for a particular set of sensors, adding a sensor generates significant amounts of work. It is possible to make a system consisting of a multitude of GPS and non-GPS sensors, which would work in almost all environments, but such a system would be extremely unwieldy in terms of size, weight, and power, as well as computational complexity. In reality, different missions call for different sensor suites; therefore, as missions change, the suites need to change with them. Ideally, we could simply attach whatever set of navigation sensors we need for a particular mission to a core integration processor in order to match capabilities to the mission's needs.

Implementing such a "plug-and-play" navigation system, however, requires research and development in the underlying integration algorithms as well as in the integration architecture (including both hardware and software) that connects and combines inputs from multiple physical sensors. The navigation research community has a growing interest in this topic. For example, DARPA has just released a broad area announcement for a program that seeks to "develop the architectures, abstraction method, and navigation filtering algorithms needed for rapid integration and reconfiguration of any combination of sensors."[24] Although flexible system integration presents a difficult challenge, it will have significant payoff to military users if we can make systems capable of navigating in almost any environment—but those systems must also be practical in terms of size, weight, power, and cost.

ANT Center researchers have developed technologies that will begin producing the all-source navigation algorithm and sensor suite we need to field an all-source navigation system. The Air Force must continue to invest in integration algorithms, sensor capabilities, and modular technologies if it wishes to succeed in maintaining precision navigation in GPS-denied environments. ✪

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Notes

1. John W. Moyle, "The Space and Air Force: One Pathway to the Future," *Air and Space Power Journal: Chronicles Online Journal*, accessed 15 March 2011, http://www.airpower.maxwell.af.mil/airchronicles/cc/moyle.html.

2. Alan Cameron, "Perspectives—June 2008," 24 June 2008, GPS World, http://www.gpsworld.com/gnss-system/perspectives-june-2008-7254.

3. Michael P. Pillsbury, PhD, *An Assessment of China's Anti-satellite and Space Warfare Programs, Policies and Doctrines*, Report to the US-China Economic and Security Review Commission, 19 January 2007, http://www.uscc.gov/researchpapers/2007/FINAL_REPORT_1-19-2007_REVISED_BY_MPP.pdf.

4. The term *navigate* means "to record, plan, and control the position and course of [a ship or an aircraft]." It is derived from the Latin *navigare*, which comes from *navis* or "ship" and *agere*, "to direct." *Webster's II: New Riverside University Dictionary*, 1988, s.v. "navigate."

5. A common tool for direction finding—a magnetic compass—was introduced in China in the twelfth century. People commonly determined distance by noting the ship's speed and time. See Pratap Misra and Per Enge, *Global Positioning System: Signals, Measurements, and Performance* (Lincoln, MA: Ganga-Jamuna Press, 2001).

6. United States Air Force Chief Scientist (AF/ST), *Report on Technology Horizons: A Vision for Air Force Science and Technology during 2010–2030*, vol. 1, AF/ST-TR-10-01-PR (Washington, DC: Headquarters US Air Force, Office of the USAF Chief Scientist, 15 May 2010), 76, http://www.aviationweek.com/media/pdf/Check6/USAF_Technology_Horizons_report.pdf.

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8. Senate, *Statement by Dr. Jane A. Alexander, Acting Director, Defense Advanced Research Projects Agency, before the Subcommittee on Emerging Threats and Capabilities, Committee on Armed Services, United States Senate*, 107th Cong., 1st sess., 5 June 2001, 9, http://armed-services.senate.gov/statemnt/2001/010605alex.pdf.

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10. Ryan J. Eggert and John F. Raquet, "Evaluating the Navigation Potential of the NTSC Analog Television Broadcast Signal" (presentation, Proceedings of the 17th International Technical Meeting of the Satellite Division of the Institute of Navigation [ION GNSS 2004], Long Beach, CA, 21–24 September 2004), 2436–46; Jonathan McEllroy, John F. Raquet, and Michael A. Temple, "Use of a Software Radio to Evaluate Signals of Opportunity for Navigation" (presentation, Proceedings of ION GNSS 2006, Fort Worth, TX, 26–29 September 2006); Richard K. Martin, Jamie S. Velotta, and John F. Raquet, "Bandwidth Efficient Cooperative TDOA Computation for Multicarrier Signals of Opportunity," *IEEE* [Institute of Electrical and Electronics Engineers] *Transactions on Signal Processing* 57, no. 6 (June 2009): 2311–22; and Wilfred Noel, "Indoor Navigation Using OFDM [Orthogonal Frequency-Division Multiplexing] Signals" (master's thesis, Air Force Institute of Technology, AFIT/GE/ENG/11-30, March 2011).

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12. For real-world demonstrations of AM radio station navigation compared to GPS-based navigation, see Timothy D. Hall, Charles C. Counselman III, and Pratap Misra, "Instantaneous Radiolocation Using AM Broadcast Signals" (presentation, Proceedings of ION NTM, Long Beach, CA, 22–24 January 2001), 93–99.

13. One such scheme is detailed in Jason Crosby, "Fusion of Inertial Sensors and Orthogonal Frequency Division Multiplexed (OFDM) Signals of Opportunity for Unassisted Navigation" (master's thesis, Air Force Institute of Technology, AFIT/GE/ENG/09-11, March 2009).

14. To use a signal to determine position, one should know its origin. Radio-frequency fingerprinting helps associate signals with their particular transmitter. See William C. Suski et al., "Using Spectral Fingerprints to Improve Wireless Network Security" (presentation, Global Telecommunications Conference, 2008: IEEE GLOBECOM 2008, New Orleans, LA, December 2008).

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16. William F. Storms and John F. Raquet, "Magnetic Field Aided Vehicle Tracking" (presentation, Proceedings of ION GNSS 2009, Savannah, GA, 22–25 September 2009).

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18. Michael Veth and John Raquet, "Fusing Low-Cost Image and Inertial Sensors for Passive Navigation," *Navigation* 54, no. 1 (Spring 2007): 11–20.

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20. Capt Adam D. Weaver, "Predictive Rendering: A New Vision-Aided Approach for Autonomous Aerial Refueling" (master's thesis, Air Force Institute of Technology, AFIT/GE/ENG/09-45, March 2009).

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22. 2nd Lt Erich Lichtfuss, "Indoor Navigation Using Vision and Radio Ranging" (master's thesis, Air Force Institute of Technology, AFIT/GE/ENG/11-23, March 2011).

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24. Strategic Technology Office, *Broad Agency Announcement: All Source Positioning and Navigation (ASPN)*, DARPA-BAA-11-14 (Arlington, VA: Defense Advanced Research Projects Agency, Strategic Technology Office, November 2010), 5, https://www.fbo.gov/download/b9e/b9e293bc25ab6cc1f7ad0601415bf5df/DARPA_BAA_11-14_All_Source_Positioning_and_Navigation_(ASPN).pdf.

Achieving the Air Force's Energy Vision

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The US Air Force is the largest consumer of energy in the federal government, spending $9 billion in 2008 to fuel aircraft and ground vehicles as well as provide energy to installations.[1] In that same year, the Air Force's fuel bill of $7 billion amounted to more than half of the US government's total fuel cost.[2] Because of the critical and central role that energy plays in completion of the Air Force's mission, the secretary of the Air Force has developed an Air Force energy plan supported by three pillars—"Reduce Demand," "Increase Supply," and "Culture Change"—and guided by the energy vision "Make Energy a Consideration in All We Do" (fig. 1). In response to the Air Force's energy program and vision, Air Force Institute of Technology (AFIT) researchers are helping realize the first two pillars by developing a new academic specialization in alternative energy, designing hybrid-electric remotely piloted aircraft (RPA), testing synthetic fuels, creating a new course of study concentrating on managing fuels distribution, and conducting research on the storage, management, and distribution of fuel. The third pillar, "Culture Change," lies outside the scope of this article. Given the success of the academic programs and promising research results, the Air Force should continue to expand energy-related curricula and research at AFIT. Increased support would allow establishment of an energy-focused research center at AFIT that could help the Air Force tackle its energy-related challenges.

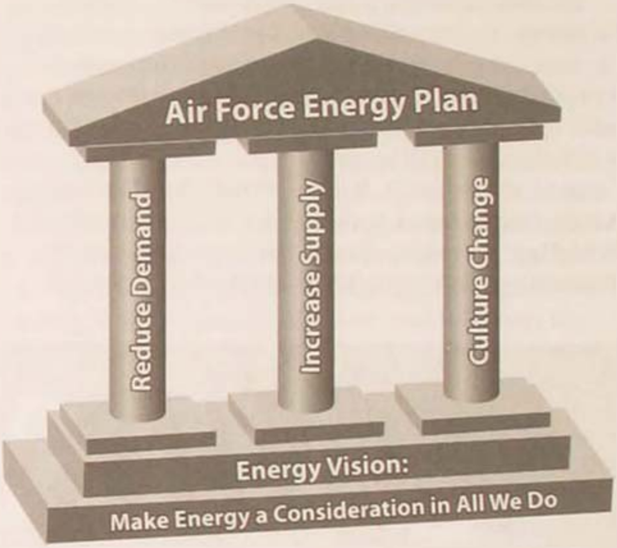

Figure 1. Three pillars of the Air Force energy plan. (Reprinted from *Air Force Energy Plan 2010* [Washington, DC: Assistant Secretary of the Air Force for Installations, Environment, and Logistics, 2010], 7, http://www.safie.hq.af.mil/shared/media/document/AFD-091208-027.pdf.)

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Academic Specialization in Alternative Energy

Researchers are investigating possibilities for alternative energy (e.g., hybrid-electric systems, fuel cells, biofuels, and solar power) in the United States to reduce our dependency on foreign oil. Most of this research has examined automotive transportation and ground-based facilities, but this article discusses the rising interest of and momentum from the military and industry in applying clean, renewable energy to air and space applications. The strategic plan of the American Institute of Aeronautics and Astronautics for 2009–13, which emphasizes energy as well as air and space, lists "Improve Aerospace Energy Efficiency and Advance New Energy Technologies" as a strategic imperative. According to this imperative, "AIAA must provide a collaborative, information-sharing environment to ensure that the best technical professionals and most creative innovators are focused on fuel efficiency challenges facing the aerospace industry and on emerging opportunities to contribute to future sources of clean, affordable energy."[3] The Air Force, defense contractors, and industry need researchers and engineers who have technical expertise in the fields of aerospace engineering and alternative energy. Many universities offer excellent programs in these disciplines, but very few emphasize merging the two. AFIT is bridging the gap in academia by enhancing its curriculum with energy-related courses, hiring faculty members with experience in both fields, and expanding its laboratory facilities.

In response to the Air Force's pressing need for engineers with educational backgrounds in alternative energy and aerospace engineering, AFIT has developed an academic specialization in alternative energy systems within its aeronautical engineering and astronautical engineering master's degrees. This specialization, an extension of the two current master's degrees, requires courses in energy, optimization, and air and space design. The specialization seeks to provide a coherent course of study for aerospace engineering students interested in pursuing research topics in alternative energy and advanced propulsion systems for micro air vehicles (MAV); small RPAs; and high-altitude, long-endurance aircraft. Two students completed the sequence in 2010, and six more are expected to do so in 2011.

Two other universities, Wright State University and the University of Dayton via the highly successful Dayton Area Graduate Studies Institute program, are contributing to academic specialization in alternative energy. The state of Ohio approved both universities' proposals to offer master's degrees in clean and renewable energy, and both have developed courses that AFIT students may take to fulfill requirements for this specialization. The collaboration allows them to receive instruction at local civilian schools and leverage research already begun at the other universities.

As part of the specialization, AFIT has developed an independent-study course to educate students on methods of analyzing the performance of small RPA propulsion system components such as electric motors, advanced batteries, internal combustion engines (ICE), and fuel cells. As interest in the new academic specialization increases, the institute plans to develop a laboratory course on the fundamentals of fuel cell technology, motors, advanced batteries, and ultracapacitors.

AFIT is playing a critical role in meeting Air Force and industry demand for more engineers trained in alternative energy and aerospace engineering. These new engineers will help the Air Force implement the energy plan's call for reducing demand by increasing the efficiency of propulsion systems and augmenting the supply of energy via alternate fuels. Its strategic location near the Air Force Research Laboratory (AFRL) at Wright-Patterson AFB and numerous air and space contractors allows students to obtain practical work experience without relocating. The fact that this new program offers students a "hybrid" degree in energy and aerospace disciplines makes it unique.

Hybrid-Electric Remotely Piloted Aircraft

Industry members and university researchers are exploring new propulsion means such as hybrid-electric systems for air and space applications. Some hybrid-electric designs use an ICE and electric drive system whereas others are based on fuel cells. At the 2009 Experimental Aircraft Association's AirVenture Oshkosh, German aircraft designer and builder Flight Design displayed a parallel hybrid-electric propulsion system with an ICE and electric motor (fig. 2) for a general aviation aircraft. A battery-powered 30 kilowatt (kW) electric motor provides boost power to a downsized 86 kW Rotax 914 engine for takeoff and climbing.[4] The power-assist parallel hybrid configuration allows the pilot to stretch a glide with electric power in the event of engine failure. For large RPAs, AeroVironment is hybridizing a hydrogen-burning piston engine with an electric drive system on its high-altitude, long-endurance Global Observer aircraft.[5] Previously, three researchers at the University of California–Davis developed a conceptual design of a small hybrid-electric RPA that laid the foundation for a prototype of such an aircraft currently in development at AFIT.[6]

Figure 2. Flight Design's hybrid-electric propulsion system. (Reprinted by permission from Jason Paur, "Hybrid Power Comes to Aviation," *Wired.com*, 28 July 2009, http://www.wired.com/autopia/2009/07/hybrid-aviation.)

Former AFIT student Ryan Hiserote compared three distinct parallel hybrid-electric conceptual designs for a small RPA, each with three battery-discharging profiles, for a total of nine configurations.[7] His analysis determined that a configuration using an ICE, an electric motor, and a clutch to disengage the engine during electric-only quiet operation was the most suitable for a typical five-hour intelligence, surveillance, and reconnaissance (ISR) mission. The engine is shut off during the ISR mission segment to reduce the aircraft's acoustic signature. Military and civilian students at AFIT in the Aeronautics and Astronautics Department, under the direction of Assistant Professor Fred Harmon, are designing a prototype of the hybrid-electric RPA based on the two-point conceptual design, which includes an ICE sized for cruise speed as well as an electric motor and a battery pack sized for a slower endurance speed (i.e., loiter). The parallel hybrid-electric design gives the vehicle longer time on station and greater range than electric-powered vehicles, together with smaller acoustic and thermal signatures than gasoline-powered vehicles. The resulting design takes the form of a 13.6 kilogram RPA that uses 40 percent less fuel than a conventional ICE-powered aircraft and that includes enhanced capability supplied by a "quiet" mode during ISR operations, utilizing only the electric system. These efforts illustrate the growing interest in applying hybrid-electric technology to air and space systems and the benefits that those systems can offer war fighters.

In addition to hybrid-electric systems with hydrocarbon-powered engines, numerous companies and universities are researching fuel-cell-based systems for aviation applications. Boeing recently flew a manned aircraft (two-seat Dimona motor-glider with a 16.3-meter wingspan) powered by a proton-exchange-membrane fuel cell/lithium-ion-battery hybrid propulsion system.[8] The company's researchers believe this type of fuel cell technology could power small manned and remotely piloted vehicles. For large commercial aircraft, designers could apply solid-oxide fuel cells to secondary power-generating systems, such as auxiliary power units. The Georgia Institute of Technology has designed, built, and flown a fuel-cell-powered RPA.[9] The Navy recently flew a small RPA, the Ion Tiger, powered by a 500-watt fuel cell.[10] The AFRL has flown a fuel-cell-based system on a Puma RPA. Under a small-business-innovation research contract with the AFRL, modification of the original battery-only-powered Puma with a fuel cell hybrid system expanded its mission capabilities by tripling flight endurance time from three to nine hours.[11] In July 2009, the experimental Antares DLR-H2 became the world's first manned vehicle to take off under fuel cell power.[12] Not long ago, AFIT initiated an effort to develop a conceptual design tool to better understand the advantages and tradeoffs of using fuel cells in MAVs.[13] The tool integrates precise analyses of aerodynamics, propulsion, power management, and power sources to determine the endurance capability of a given mission for an MAV.

These hybrid-electric system efforts, whether based on ICEs or fuel cells, clearly reflect the interest in applying alternative-energy concepts to aircraft applications. The previously mentioned designs will prove useful, depending on mission requirements as well as size and type of aircraft. For example, as described earlier, AFIT researchers are testing a prototype of a hybrid-electric system for a small RPA to demonstrate its usefulness during a typical ISR mission. Furthermore, a current AFIT student's work on a conceptual design of a hybrid-electric system for a trainer aircraft will determine how much fuel and energy it can save during a typical training mission. The Air Force should support the expansion of AFIT's research on fuel-cell-based systems to ascertain the improvement in range and endurance for small RPAs and MAVs. For larger aircraft, such systems may be useful for auxiliary power units. Hybrid-electric systems will contribute to the first pillar of the energy plan by helping lessen the demand for energy.

Testing Synthetic Fuel

AFIT is contributing to the second pillar—increasing the supply of energy—by conducting research into alternate fuels. Aviation fuel is a substantial expense for both the Air Force and commercial airlines. In 2006 fuel became the largest element of operating costs for US airline carriers for the first time in history.[14] As the most prolific consumer of aviation fuel in the federal government, the Air Force uses approximately 2.5 billion gallons per year.[15] The service can reduce fuel costs by using alternate fuels (e.g., Fischer-Tropsch [FT] fuels), designing more efficient engines or new propulsion systems, or designing more aerodynamic configurations and lighter structures.[16]

Commercial industry and the government have both established organizations to research and certify the use of alternate fuels. A coalition known as the Commercial Aviation Alternative Fuels Initiative strives to enhance energy security and environmental sustainability for aviation by engaging the emerging alternative jet fuels industry to use those fuels in commercial aviation.[17] Bill Harrison, technical adviser for fuels and energy for the Propulsion Directorate at the AFRL, also stresses the need to increase the supply of domestic fuels by researching, testing, and certifying new alternative/domestic fuels.[18] Alternative fuels could replace many traditional ones such as JP-5, JP-7, and JP-8. For example, in August 2007 the B-52 aircraft was certified for a 50/50 blend of a synthetic fuel and JP-8.[19] The Air Force also stood up the Alternative Fuels Certification Office in 2007 with a charter from the secretary of the Air Force to manage certification of all Air Force platforms (over 40 types), support equipment, and base infrastructure on a 50/50 blend of FT fuel and JP-8.[20] Nearly the entire Air Force fleet has been certified to fly on a synthetic fuel blend.

AFIT actively researches the replacement of traditional jet fuels with alternatives. Jet fuels fall into the broad class of hydrocarbon materials referred to as kerosene fuels.[21] Compared to traditional jet fuels produced from petroleum (e.g., JP-8), FT fuels are synthetically derived from other sources such as coal, natural gas, or biomass—the product of a catalyzed chemical process that initially converts feed fuels into carbon monoxide and hydrogen and then combines those chemicals into longer-chain hydrocarbon molecules. Theoretically, the energy content of these fuels is sufficient to replace traditional ones, but we need more research on their use in devices originally designed for traditional jet fuels.[22] AFIT is researching the use of FT fuels in an ultracompact combustor in the Combustion Optimization and Analysis Laser laboratory, which has several diagnostic techniques available (e.g., measuring the amount of unburned hydrocarbon and nitrogen oxides) to analyze the performance of these new fuels. Initial results show promise and demonstrate that FT fuels can substitute for traditional jet fuels.

Academic Course of Study in Petroleum Management and Research into Fuels Distribution

Recently, AFIT developed a specialized fuels-management track in its master of science program in logistics and supply chain management. In the fall of 2010, five Air Force fuels officers began this new course of study, which encompasses inventory models, demand forecasting, supply-chain resiliency, alternative fuels, environmental issues, and the transportation, distribution, and storage of petroleum. Graduates of this program will be assigned to the Air Force Petroleum Agency, the Defense Logistics Agency, and other petroleum-management positions on major command staffs.

Students, both domestic and international, from AFIT's Department of Operational Sciences have conducted numerous in-depth, cutting-edge studies on fuels. For example, Maj David Mazzara did a cost-benefit analysis of air refueling of RPA systems.[23] Maj James Nicholson investigated the cost-effectiveness of replacing petroleum-based diesel-like fuels with biodiesel fuels in Air Mobility Command, determining the price needed to offset the cost of producing biodiesel if the price of traditional fuel increases.[24] Lt Col Juan Salaverry developed a model for forecasting jet fuel prices in his home country of Argentina.[25] Maj Murat Toydas developed two nonlinear optimization models that examined the trade-off between departure fuel weight and loaded cargo for a given origin, destination, and tanker base location.[26] And Lt Evren Kiymaz conducted a study that measured airlift fuel efficiency.[27] All of these studies illustrate methods either to decrease fuel demand or to increase its supply.

In one very successful study, Maj Phil Morrison, a recent graduate of AFIT's Advanced Study of Air Mobility program, completed research on reballasting the KC-135.[28] He hypothesized that shifting ballast fuel out of the forward-body fuel tank and compensating by adding weight (such as armor) elsewhere on the plane would yield two significant benefits: (1) tankers could off-load more fuel to receiver aircraft, and (2) the Air Force would reap significant savings through improved fuel economy of its KC-135 tanker fleet. Major Morrison's research indicated that, if implemented, his proposal would pay for itself in less than two years and mitigate an additional $14 million in fuel cost each year thereafter. The Air Force recently committed funds to make the ballasting change in the KC-135.

Conclusion and Recommendations

The Air Force is striving to lower its energy expenditures and raise energy security by reducing demand, increasing supply, and changing its culture. AFIT researchers are contributing to the first two pillars of the energy plan by developing new curricula that concentrate on alternative energy and fuels, designing hybrid-electric propulsion systems, testing synthetic fuels to replace traditional fuels, and advancing research in the area of fuel distribution and management. AFIT military and civilian graduates who have backgrounds in aerospace engineering, alternative energy, and fuel management will assume technical leadership positions and possess the knowledge to leverage technologies and tools for critical air and space applications to help the Air Force carry out its energy plan.

The Air Force needs to fully support AFIT in this endeavor. AFIT should expand its curricula to incorporate more courses on energy and fuels as well as construct laboratories to test hybrid-electric systems, fuel cells, and synthetic fuels. Conceptual design tools need improvement in order to analyze options for future Air Force aircraft such as hybrid-electric trainers and RPAs. AFIT also needs to conduct further research on fuel-cell-based systems to determine the enhancement in range and endurance for small RPAs and MAVs. For larger aircraft, AFIT should conduct more research into how fuel-cell-based systems may prove useful for auxiliary power units. Additionally, if the institute received appropriate support, it could establish an energy-focused interdisciplinary research center. Clearly, AFIT has a vital role to play in helping the Air Force achieve its energy vision. ✪

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AIR FORCE INSTITUTE OF TECHNOLOGY

Unintended Consequences

Potential Downsides of the Air Force's Conversion to Biofuels

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The desire to reduce US dependence on foreign energy, ongoing environmental concerns, and the rising cost of petroleum have sparked significant development of "greener" alternative and renewable energy sources such as alcohol-based biofuels. To address these issues, the Department of Defense (DOD) has moved to diminish its reliance on petroleum for fueling aircraft and ground equipment. The US Air Force, in alignment with DOD objectives, has initiated several goals for reducing its use of energy: (1) decrease the use of petroleum-based fuel by 2 percent annually for the vehicle fleet, (2) increase the use of alternative fuel in motor vehicles annually by 10 percent, (3) certify all aircraft and weapon systems for a 50/50 alternative fuel blend by 2011, and (4) have Air Force aircraft flying on 50 percent alternative fuel blends by 2016.[1] This aggressive timetable moves the world's single largest petroleum consumer, the DOD, squarely into the alternative energies market. As the world's most prodigious fuel consumer, the DOD would likely drive segments of the aviation and motor fuels markets around the world to meet the demand for newly formulated alternative fuels and to convert existing fuel-delivery systems to support the new market. Although conversion to alternative fuels can clearly lower the production of carbon dioxide, the risks that potential fuel spills pose to soil and groundwater are only now becoming clear.

This article contends that we have not adequately addressed the potential impacts of these alternative fuels on the environment. Presently, research indicates that the risks caused by subsurface environmental contamination might actually increase with the large-scale introduction of alternative fuels. Additionally, future fuel supplies and storage systems may experience troublesome fouling due to the more biologically reactive nature of alternative fuels. Therefore, prudence demands that the Air Force use the most current research and actively support new research to understand the implications of accelerated use of biofuels, in-

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cluding environmental and other risks associated with spills and impairment of the systems that transport, store, and consume these fuels. In view of these implications, this article proposes a way ahead to ensure that large-scale incorporation of alternative fuels into the DOD's massive fuel stream does not inadvertently result in contaminated groundwater, generation of explosive gas near the thousands of DOD fuel distribution and storage facilities, or adverse operational consequences due to microbial spoilage of fuels.

Subsurface Environmental Impacts

Across the DOD, fuel systems safely move millions of gallons of fuel to and from massive above- and below-ground storage tanks, yet systemwide leaks and spills continue to occur despite over 100 years of technological development in fuel storage and distribution. Every connection along thousands of miles of pipe, every control valve, and every seam in every tank represent a potential source for leakage. These fuel spills and leaks from storage tanks, pipes, tanker vehicles, and associated equipment have contaminated soil and groundwater with a class of environmentally hazardous compounds called aromatic hydrocarbons. Of these compounds, several—including benzene—are known carcinogens.[2] In soil and groundwater, levels of aromatic hydrocarbons such as benzene and other dissolved and vapor contaminants are typically lowered through natural processes. Naturally occurring underground (i.e., subsurface) bacteria can transform hydrocarbon contaminants such as benzene, toluene, ethylbenzene, and xylene isomers (BTEX) and their breakdown products such as methane into harmless substances. Some bacteria use these organic contaminants—sometimes in combination with an oxidizing agent such as oxygen—as carbon and energy sources (i.e., "food" essential for their survival and growth).

As the field data below demonstrates, introducing alternative fuels into a leaking fuel mixture significantly modifies the complex ecological relationship among bacteria, BTEX and other contaminants, and oxidizers—increasing the possibility of groundwater contamination. Previous research on such contamination using computer modeling techniques focused on bacteria's ability to process BTEX contaminants in the presence of ethanol, a widely preferred alternative motor fuel. However, the computer models generally assumed the presence of oxidizers (oxygen) not commonly dominant in soil and groundwater at fuel-spill sites, resulting in an overly favorable view of the environmental suitability of alternative fuels.[3] Recent research reveals a more troubling picture.

A field experiment at Vandenberg AFB, California, yielded a surprising result when researchers studied subsurface contamination that might arise from a slow release of gasoline blended with ethanol into groundwater, such as might result from a hard-to-detect leak of an ethanol/gasoline mix from a fuel-storage tank.[4] The field study was designed to compare the fate of BTEX compounds with or without corelease of ethanol. Researchers conducted two experiments simultaneously in an aquifer at Vandenberg, where sulfate functioned as the predominant oxidizing agent—as was the case for many petroleum spill sites nationwide.[5] One experiment involved the nine-month continuous injection of water laced with small amounts (one to three milligrams per liter [mg/L]) of the BTEX-class compounds benzene, toluene, and ortho-xylene. The second (simultaneous) experiment in an adjacent location included 500 mg/L of ethanol with the BTEX compounds. Levels of BTEX contaminants, particularly the cancer-causing compound benzene, were monitored along with the levels of oxidizing agents (particularly oxygen and sulfate), degradation products (including methane), and, in the case of the second study, ethanol. Results for the first experiment were as expected, with the underground plume of contaminants spreading for about four months, after which the benzene contamination retracted almost completely due to biodegradation caused by naturally occurring bacteria.

The outcome of the second experiment proved striking by comparison. In the second location, where ethanol was introduced along with the benzene contaminant, the area of contamination expanded, as observed in the first experiment; however, the benzene contamination did not retract nearly as much. Benzene levels in the second experiment degraded more slowly, and copious amounts of methane were generated since the native bacteria shifted most activity to the more easily degradable ethanol. This phenomenon held true for those bacteria utilizing the commonly occurring oxidizer sulfate, as well as those microbes able to biodegrade the contaminants without an oxidizer (some of which produce methane). This result helped confirm the hypothesis that the original computer model assumptions did not apply in all instances and that results from actual field experiments provide more useful insight into the ability of natural processes to detoxify BTEX compounds in the presence of the widely preferred alternative fuel ethanol. The field experiment also demonstrated that ethanol may degrade to create significant amounts of methane. In real spills with much greater amounts of ethanol than released in the experiment, methane generation around the spilled fuel could create significant amounts and flows of this flammable gas within the soil. If the methane itself is not oxidized by native soil microbes, in some circumstances spills of biofuels might lead to explosive gas mixtures reaching building basements, buried infrastructure, or the ground's surface.

Adding ethanol to petroleum appears to slow the biodegradation rates of hazardous BTEX compounds; furthermore, contaminants exist for longer periods and travel greater distances than predicted by prior modeling. In short, this finding was irrefutable, given the clear and detailed field evidence from a site quite typical of fuel spills. We can now use more soundly based computer modeling to extrapolate from the field results to other scenarios than those examined experimentally. Air Force Institute of Technology (AFIT) researchers developed such a model, which incorporated the important processes revealed in the Vandenberg studies. Model simulations showed the long-term effect of adding ethanol to fuel. Researchers used the model to simulate two spills lasting 30 years—one for benzene only, the other for a mixture of benzene and ethanol. The model confirmed the data from the field experiment: after simulating 30 years, the benzene plume with ethanol is substantially longer than the one without ethanol.

Butanol, a type of alcohol that is an alternative candidate biofuel additive, offers a number of advantages over ethanol. Butanol's energy density is nearly equivalent to that of gasoline, while the energy density of ethanol is 34 percent lower.[6] Compared to ethanol, butanol is less volatile and corrosive, has less affinity for water, and is compatible with today's pipeline and fuel-storage infrastructures.[7] Butanol is similar enough to gasoline that it can "be used directly in any gasoline engine without modification and/or substitution."[8] Based on this fact, and in consideration of the previous field study at Vandenberg that examined ethanol's effects in groundwater, AFIT researchers conducted model simulations to investigate what would happen if butanol were used as a biofuel. Unfortunately, the use of assumptions that appeared reasonable based on past laboratory and modeling research produced a modeling prediction that butanol would have an even greater negative impact on the fate of benzene, the most hazardous compound in gasoline, than ethanol did.[9] However, researchers needed to make many assumptions to conduct the simulations. Given the importance of this problem, we believe that it merits field research in real geologic media to provide insights and confirm or refine modeling assumptions before we can make a more confident prediction of the environmental effects of fuels that contain butanol.

Biofouling Potential

In addition to effects on the subsurface environment, the increased use of biofuels may result in the seemingly curious but extremely important problem of biofouling—the microbial spoilage of fuel. The combustion characteristics of biofuels closely resemble those of petroleum-based fuels; however, their chemical compositions are quite different.[10] Biofuels (such as biodiesel) include components that are both more water soluble and more degradable by microorganisms. Currently, fuel-handling facility operators of pipelines, storage tanks, and trucks take care to minimize contact between water and fuel because of potential microbial growth at water/fuel interfaces; however, it is impossible to exclude water completely from the systems. Simple atmospheric vents and the related condensation from moist air are sources of moisture that can end up as liquid water in fuel systems. Low levels of fuel spoilage and microbial fouling, which occur now, represent persistent, sometimes critical, problems for fuel handlers. Probably no fuel system is completely free of microbes and the possibility of fuel spoilage.

Though typical practical examinations may not detect organisms in fuel, for many years AFIT has conducted laboratory and field research to investigate fuel microbial quality. AFIT and Air Force Research Laboratory researchers determined that no single organism dominated the population recovered from aviation fuel tanks and that relatively little overlap existed in the composition of microbial populations from different geographic locations or types of aviation fuel.[11] Many different species of bacteria and fungi are capable of metabolizing fuel components, resulting in significant degradation of fuel quality and potential damage to fuel system components through either plugging or corrosion problems. This fact indicates that the possible spoilage problem is multifaceted, but research clarifying the most common microbial culprits allows better insight into how to reduce the effects on fuel quality.

Increased water solubility and degradability of biofuel components magnify the potential for biofouling already seen with conventional fuels. Current nuisance problems could expand into major issues with greater use of biofuels. Fouling of storage and transport facilities could become a significant and expensive dilemma. Fouling of aircraft could have tragic consequences; indeed, in the late 1950s at least one crash was partially attributed to microbial plugging of the fuel system.[12] Fortunately, after the crash, a deicer—subsequently added to fuel—turned out to have significant antimicrobial properties, eliminating the problem for many years. Changes in fuel composition (JP-4 versus JP-8) and deicers due to toxicity concerns may have prompted a resurgence of microbial contamination. Increased biofuel usage may further enhance the possibility of microbial contamination and spoilage. Clearly, we need to identify the types of microbes likely to pose the most significant issues with new fuels before these matters become critical; furthermore, research should be able to pinpoint the optimal ways to minimize spoilage of new fuels for different fuel-handling or storage facilities. For example, high-flow systems may be relatively easy to keep clean simply because they are dynamic and because fuels move through them before problems have time to develop. Long-term static storage tanks, however, such as those associated with emergency power-generator systems, may pose serious difficulties involving contamination and spoilage.

At the very least, biofuel use will require more extensive monitoring and more rigorous housekeeping on the part of fuel handlers. Prevention of a biofuel catastrophe will demand effort well beyond the level required for oil-based fuels as well as new research to supply the knowledge base to support that effort.

Recommendations

The latest research clearly indicates that alternative fuels represent a potential threat to soil and groundwater and that biofuel spills may lead to significant generation of methane gas and extend the persistence of cancer-causing fuel compounds such as benzene in water supplies. Additionally, since benzene and other contaminants degrade more slowly in the leaking area when alternative biofuels are present, the contamination plume can spread greater distances before bacterial processes can reduce contaminant levels. Finally, because biofuels are more hygroscopic and biodegradable than current fuels, fuel users and storage and distribution systems may experience greater mission degradation due to fuel biofouling.[15] We recognize the urgency of shifting to biofuels but suggest that doing so creates an equally urgent need for research to produce the knowledge we need to adjust our fuel-management practices and safety protocols in order to maintain high standards for protection of facilities, equipment, personnel, and the environment. We thus recommend the following actions to mitigate possible contamination of groundwater and soil as well as biofouling of fuel-management systems:

1. Develop technologies to reduce, monitor, and mitigate spills and leaks, designing them specifically for biofuel distribution and storage systems. This process includes upgrading critical fittings and connections among processing, distribution, storage, and consumption facilities to ensure that the most likely sources of leaks are modified to assure compatibility with the new fuel mixture.

2. Expand research that furthers our fundamental understanding of the environmental effects and biofouling potential of biofuels.

Conclusion

The Air Force's efforts in research and development of biofuel-compatible platforms to meet the DOD's goals for decreasing its use of energy are reasonable, given the number of obvious advantages that biofuels offer. However, we do not yet sufficiently understand a number of the disadvantages of biofuels. Only when researchers challenged the assumptions of computer modeling with an actual field study at a representative test site at Vandenberg AFB did the potential for more environmental contamination appear. The study clearly showed that contamination plumes of carcinogens such as benzene could persist and expand in the presence of ethanol but disappear in its absence.[14] Similarly, field and lab research at AFIT has been a key element in understanding biofouling of petroleum-based fuels, suggesting that biofouling will become even more serious for biofuels. Because the DOD has not supported additional research on these critical topics, it is imperative that the Air Force investigate them further.

In the future, our senior leadership will confront a series of decisions regarding the type and mixture of biofuels that our ground and air fleets should use. Presently, the Air Force is conducting research to facilitate decisions in certain areas, such as compatibility of alternative fuel blends with end-user systems, motors, and turbine engines. However, researchers have yet to sufficiently explore other important questions, such as those regarding "nonobvious" environmental implications and biofouling. At a minimum, the Air Force should support additional field research to improve our understanding of the probable subsurface effects of biofuels and to create opportunities for developing new methods of monitoring and remediating such effects. The service should also continue to investigate the microbial spoilage of biofuels and develop mitigation methods. If the DOD and Air Force are compelled to use biofuels before completing more research, we recommend monitoring some of the biofuel storage and use locations in considerably more detail than normal, perhaps as an "applied research" project, to help identify and bound the significance of the issues we raise here. Only through well-controlled laboratory and field research and applied research studies will the DOD and Air Force gain insight into these matters and develop new technologies that will allow senior leadership to make informed decisions and thus avoid unpleasant surprises. ✪

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Notes

1. Air Force Policy Memorandum 10-1.1, *Air Force Energy Program Policy Memorandum*, 16 June 2009, 6–7, accessed 13 January 2010, http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA502661.

2. American Conference of Governmental Industrial Hygienists, *2003 TLVs and BEIs: Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices* (Cincinnati: ACGIH, 2003), 15.

3. Diego E. Gomez and Pedro J. J. Alvarez, "Modeling the Natural Attenuation of Benzene in Groundwater Impacted by Ethanol-Blended Fuels: Effect of Ethanol Content on the Lifespan and Maximum Length of Benzene Plumes," *Water Resources Research* 45 (2009): W03409, doi:10.1029/2008WR007159.

4. Douglas M. Mackay et al., "Impact of Ethanol on the Natural Attenuation of Benzene, Toluene, and O-xylene in a Normally Sulfate-Reducing Aquifer," *Environmental Science and Technology* 40, no. 19 (2006): 6123–30.

5. Todd H. Wiedemeier et al., *Natural Attenuation of Fuels and Chlorinated Solvents in the Subsurface* (New York: John Wiley and Sons, 1999), 213–18.

6. Density equals energy per unit volume.

7. Lawrence P. Wackett, "Microbial-Based Motor Fuels: Science and Technology," *Microbial Biotechnology* 1, no. 3 (2008): 211–25; and Adriano P. Mariano et al., "Aerobic Biodegradation of Butanol and Gasoline Blends," *Biomass and Bioenergy* 33, no. 9 (September 2009): 1175–81.

8. Sang Yup Lee et al., "Fermentative Butanol Production by Clostridia," *Biotechnology and Bioengineering* 101, no. 2 (2008): 210.

9. Capt Khai H. Vuong, "Modeling the Fate of Groundwater Contaminants Resulting from Leakage of Butanol-Blended Fuel," AFIT/GES/ENV/10-M06 (thesis, Department of Systems and Engineering Management, Air Force Institute of Technology, Wright-Patterson AFB, OH, March 2010), accessed 13 January 2011, https://www.afresearch.org/skins/rims/q_mod_be0e99f3-fc56-4ccb-8dfe-670c0822a153/q_act_downloadpaper/q_obj_2262ab9b-e4ad-49da-ba4a-43c31778618f/display.aspx?rs=publishedsearch.

10. Jared A. DeMello et al., "Biodegradation and Environmental Behavior of Biodiesel Mixtures in the Sea: An Initial Study," *Marine Pollution Bulletin* 54, no. 7 (2007): 894–904.

11. Michelle E. Rauch et al., "Characterization of Microbial Contamination in United States Air Force Aviation Fuel Tanks," *Journal of Industrial Microbiology and Biotechnology* 33, no. 1 (2006): 29–36; and Lisa M. Brown et al., "Community Dynamics and Phylogenetics of Bacteria Fouling Jet A and JP-8 Aviation Fuel," *International Biodeterioration and Biodegradation* 64, no. 3 (June 2010): 253–61.

12. Viola H. Finefrock and Sheldon A. London, *Microbial Contamination of USAF JP-4 Fuels*, Technical Report AFAPL-TR-66-91 (Wright-Patterson AFB, OH: Air Force Aero Propulsion Laboratory, 1966), 1, accessed 13 January 2011, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=AD809366&Location=U2&doc=GetTRDoc.pdf.

13. *Hygroscopic* refers to the ability to absorb water from the surrounding environment.

14. Mackay et al. "Impact of Ethanol," 6123–30.

Jet Propellant 8 versus Alternative Jet Fuels

A Life-Cycle Perspective

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Maj Wayne C. Kinsel, USAF
Dr. Alfred E. Thal
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The Air Force is the largest user of jet fuel in [the Department of Defense (DOD)], consuming 2.4 billion gallons per year."[1] In light of environmental impacts associated with using nonrenewable fuel sources and national security concerns regarding dependency on foreign oil, it is no surprise that the United States is paying more attention to alternative fuels. Both DOD and Air Force energy strategies address the need to develop and produce such fuels. The DOD has made a commitment to energy security, establishing an energy initiative that "strive[s] to modernize infrastructure, increase utility and energy conservation, enhance demand reduction, and improve energy flexibility, thereby saving taxpayer dollars and reducing emissions that contribute to air pollution and global climate change."[2] This initiative has the following four goals:

1. Maintain or enhance *operational effectiveness* while reducing total force energy demands
2. Increase energy strategic *resilience* by developing alternative/assured fuels and energy
3. Enhance operational and business effectiveness by *institutionalizing energy considerations* and solutions in DoD *planning & business processes*
4. Establish and monitor Department-wide energy *metrics* (italics in original)[3]

In concert with the DOD's efforts, the Air Force's energy initiative features a complementary vision: "Make Energy a Consideration in All We Do."[4] The following three components of the Air Force's strategy reflect this vision:

1. *Reduce Demand* - Increase our energy efficiency through conservation and decreased usage, and increase individual awareness of the need to reduce our energy consumption.
2. *Increase Supply* - By researching, testing, and certifying new technologies, including renewable, alternative, and traditional en-

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ergy sources, the [US]AF can assist in creating *new domestic supply* sources.

3. *Culture Change* - The Air Force must create a culture where all Airmen make energy a consideration in everything they do, every day (italics in original).[5]

This article addresses the second component of the Air Force's strategy and the following specific goal: "By 2016, be prepared to cost competitively acquire 50% of the Air Force's domestic aviation fuel requirement via an alternative fuel blend in which the alternative component is derived from domestic sources produced in a manner that is 'greener' than fuels produced from conventional petroleum."[6] Several questions arise with regard to this goal. Granted, procuring "greener" fuels is a noble aspiration, but how do we evaluate such a fuel appropriately? What does the term *greener* actually mean in this situation? How do we evaluate whether a proposed biofuel is greener than the jet propellant 8 (JP-8) the Air Force currently uses? To answer these questions, this article takes a life-cycle perspective since many modern systems are complex and comprised of interdependent processes and activities. The article thus provides relevant background material regarding biofuels and applies the Economic Input-Output Life Cycle Assessment (EIO-LCA) methodology to compare petroleum-derived jet fuel (i.e., JP-8) to an alternative jet fuel derived from a coal-biomass-to-liquid (CBTL) process. The EIO-LCA approach compares the global warming potential (GWP) of those two fuel types over their entire life cycles. The EIO-LCA results give Air Force leaders a basis for evaluating alternative ways of implementing the service's energy strategy.

Background

Before presenting and discussing the EIO-LCA results, the article addresses environmental concerns associated with burning fuel; defines and characterizes the different types of alternative fuels, including the Air Force's proposed alternative fuel; and then describes life-cycle assessments (LCA).

Environmental Concerns

Greenhouse gases (GHG) trap heat in the earth's atmosphere. According to the Energy Information Administration, "These gases allow sunlight to enter the atmosphere freely. When sunlight strikes the Earth's surface, some of it is re-radiated back towards space as infrared radiation (heat). Greenhouse gases absorb this infrared radiation and trap its heat in the atmosphere."[7] Some GHGs occur naturally, but man-made sources tend to increase the levels of these gases. Carbon-dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases are the principal GHGs that enter the earth's atmosphere because of human activities, primarily as the result of the combustion of fossil fuels.[8]

Alternative Fuel

According to the DOD, "The term 'alternative' fuel is used to differentiate between diesel-type jet fuel produced from crude oil and synthetic fuel produced from non-crude oil. An alternative fuel should emulate the baseline fuel's properties to increase fungibility within military assets."[9] To be certified, alternative fuels must emulate the properties of JP-8 (i.e., yield the same energy output per unit) to ensure no degradation of flight safety.

The Air Force's alternative-fuel program seeks to produce a 100 percent "drop-in" hydrocarbon jet fuel or jet fuel blend stock. The term *drop-in* indicates that the fuel is fully interchangeable with current aviation fuels in both performance and handling so that flight safety does not degrade in any way. Typically, a blend stock consists of a 50 percent mixture of hydrocarbon (alternative fuel) and a petroleum-derived aviation fuel.[10] Regardless of their drop-in or blended status, alternative fuels are typically developed from biomass. Researchers are currently investigating three primary types of biomass to produce ground-vehicle fuels and jet fuels: sugars and starches, fats and oils, and "lingocellulosic" material. Corn is an example of a starch widely used for the production of ethanol in the United States; however, we cannot use ethanol for jet fuel because of its low flash point and heat of combustion.[11] From triglycerides—fats from oilseeds—we frequently produce biodiesel, a fuel appropriate for ground vehicles but not aircraft. Finally, switchgrass represents a lingocellulosic biomass used to produce aviation fuel. Our analysis focuses on fuels derived from this type of biomass.

Experts still debate whether biofuels are better for the environment than traditional petroleum-derived fuels. Opponents of the former consider them detrimental to the environment. For example, Timothy Searchinger, a biofuel research scholar at Princeton University's Woodrow Wilson School, notes that "previous accountings [analyses] were one-sided because they counted the carbon benefits of using land for biofuels but not the carbon costs, the carbon storage, and sequestration sacrificed by diverting land from its existing uses."[12] If current forests or grasslands are converted to cropland to produce biofuel, the conversion releases into the atmosphere carbon previously stored in trees and other plants.

Proponents of biofuels assert that producing them from biomass will result in a carbon credit. Bent Sørensen, a biofuel researcher at Roskilde University of Denmark, disagrees with Searchinger, contending that "Searchinger suggests . . it would be more scholarly to account for all carbon assimilation and release as a function of time rather than just consider biomass carbon neutral. Some of the same authors recently attacked 'second-generation' biofuels, making the prediction that biofuels will soon be derived entirely from cellulosic materials grown on marginal land." Sørensen further argues that cellulosic materials will come from residues of existing biomass-cultivation operations already functioning around the world, thereby not creating additional carbon emissions.[13]

Our analysis considered switchgrass as the biomass portion of the CBTL jet fuel. We assume that switchgrass comes from marginal or degraded lands and does not fit into the category described by Searchinger as a land-use change to produce cellulosic biomass.[14] Therefore, we assigned a carbon credit to the switchgrass portion of the CBTL jet fuel. According to a University of Dayton Research Institute report, one can take a 15 percent credit on the GHGs emitted by switchgrass when performing an LCA using biomass to produce Fischer-Tropsch (FT) jet fuels.[15] The FT process converts carbon monoxide (CO) and hydrogen (H_2) derived from coal, natural gas, or biomass into liquid fuels such as diesel or jet fuel. The research institute's report gives a GHG credit for switchgrass of 50 to 100 kilograms of CO_2 equivalents per ton of biomass.[16] This information is vital in conducting an LCA.

Life-Cycle Assessment

An LCA is a holistic analytical technique for assessing environmental effects throughout the life cycle of any product, process, or activity. In its purest form, the evaluation begins with the initial extraction of raw materials from the earth and ends once all materials are returned to the earth. Typically referred to as a cradle-to-grave approach, the life cycle includes five phases (fig. 1). These types of life-cycle approaches "help us to find ways to generate the energy we need without depleting the source of that energy and without releasing greenhouse gases that contribute to climate change."[17]

LCA models are thus important tools that facilitate green design methods for various types of projects.[18] They also provide decision makers additional information that helps define the environmental effects of activities and identify opportunities for improvements. Although numerous LCA variants exist, there are three basic types of models: process-based, EIO, and hybrid. These models typically use similar inventories of environmental emissions and resources to determine the environmental burden cor-

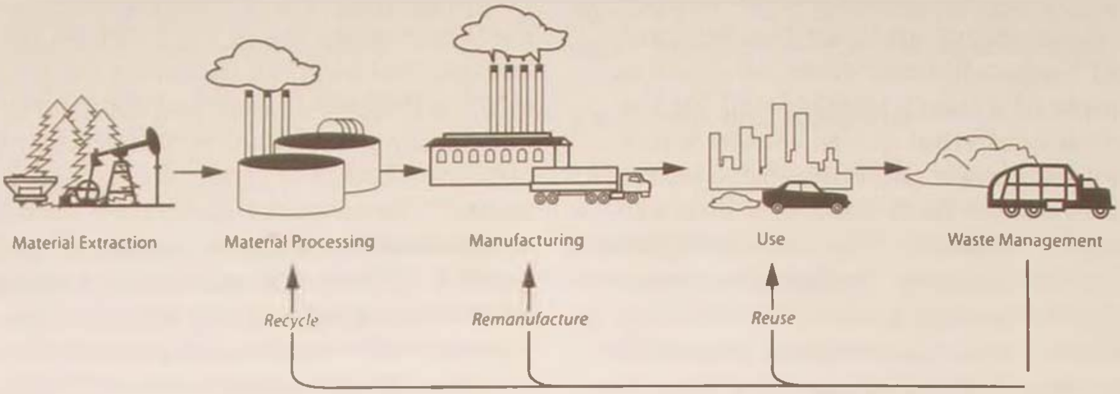


Figure 1. Life-cycle assessment phases. (Reprinted from Congress of the United States, Office of Technology Assessment, *Green Products by Design: Choices for a Cleaner Environment* [Washington, DC: Congress of the United States, Office of Technology Assessment, September 1992], 4.)

responding to any product, process, or activity. However, EIO-LCA models are usually considered more advantageous if application cost, feedback flow, or speed of analysis is important.[19]

Process-Based Life-Cycle Assessment. A process-based LCA breaks down a product or service into smaller pieces and traces each piece back to its origin. This type of LCA offers precise environmental impacts of a product or service. However, two challenges accompany process-based LCAs: the analysis boundary and circularity effects. Because of the difficulty of capturing an entire process and all of its subprocesses, researchers must take great care to determine the boundaries of what they will exclude from the analysis. Circularity effects mean that it takes a lot of "stuff" to make other "stuff." For example, "to make the paper cup requires steel machinery. But to make the steel machinery requires other machinery and tools made out of steel. And to make the steel requires machinery, yes, made out of steel. Effectively, one must have completed a life cycle assessment of all materials and processes before one can complete a life cycle assessment of any material or process."[20]

Economic Input-Output Life-Cycle Assessment. The EIO approach incorporates economic data from the US Bureau of Economic Analysis and environmental data from both the Environmental Protection Agency and Department of Energy. The EIO-LCA model is based on Wassily Leontief's Nobel Prize–winning EIO model.[21] According to Chris Hendrickson, a Carnegie Mellon University engineering professor,

> Leontief proposed a general equilibrium model that requires specifying the inputs that any sector of the economy needs from all other sectors to produce a unit of output. His model is based on a simplifying assumption that increasing the output of goods and services from any sector requires a proportional increase in each input received from all other sectors. The resulting EIO matrix has presently been estimated for developed nations and many industrializing economies.[22]

The EIO-LCA model uses EIO matrices and industry-sector-level environmental and resource consumption data to assess the economy-wide environmental impacts of products and processes.[23] The approach simplifies the complex nature of LCAs by using mathematical formulas to convert the monetary transactions between industry sectors into their environmental impacts.[24] EIO-LCA models identify direct, indirect, and total environmental effects due to production and consumption of goods and services. Total effects are the sum of direct and indirect effects.[25]

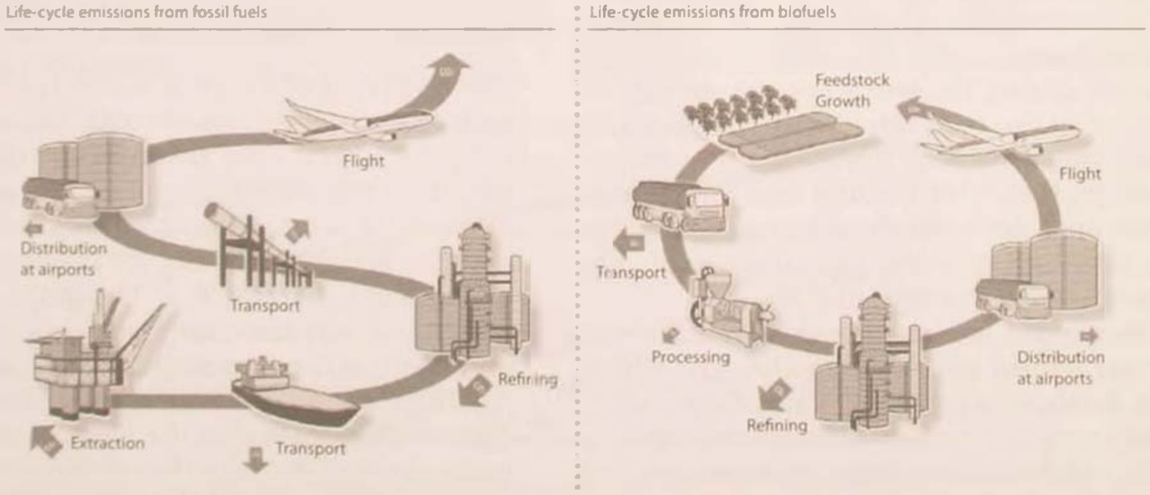
Hybrid Life-Cycle Assessment. A hybrid model integrates a process-based LCA with the EIO-LCA to produce more accurate information from an item or process; when information is not available, one can use the EIO-LCA. For example, one may know the environmental impact of the use phase of a paper cup but not the impact of the extraction phase. In that case, analysts could use the specific information for the use phase and then employ the EIO-LCA model to estimate information for the other phases. Our analysis used a hybrid LCA model.

Determining a Fuel's "Greenness"

In January 2009, the Department of Energy reported that CBTL fuels can compete economically with current petroleum-derived fuels. Specifically, a CBTL process using a mixture of 8 percent (by weight) biomass and 92 percent (by weight) coal can produce economically competitive fuels when crude oil prices equal or exceed $93 per barrel. Furthermore, CBTL fuels have 20 percent lower life-cycle GHG emissions than petroleum-derived ones. Even if CBTL is not economically competitive, the report noted that CBTL fuel has two clear advantages: (1) it has lower GHG emissions, and (2) it can be produced from domestic sources, thereby limiting the amount of foreign crude oil the United States imports.[26]

The CBTL process uses three existing technologies to convert coal and biomass into liquid fuel: gasification, FT synthesis, and carbon capture and storage. Gasification converts coal and biomass into CO and H_2, a mixture commonly referred to as "syngas." FT synthesis applies heat and pressure to syngas in the presence of a catalyst such as cobalt to create a liquid fuel.[27] The resulting CO_2 by-product is captured and stored through a relatively inexpensive process known as carbon sequestration, which promotes the alternative fuel's affordability and production of fewer GHG emissions. The remaining toxic CO is used as fuel to generate heat required for the chemical reaction. Figure 2 shows the typical life cycles of a common jet fuel produced from fossil fuels (such as jet fuel derived from crude oil) and a biofuel (such as biomass to liquid jet fuels).

Theoretically, jet fuels produced from biomass result in reduced CO_2 emissions across their entire life cycle. The CO_2 absorbed by plants during the growth of biomass is approximately equivalent to the CO_2 released into the atmosphere during


Life-cycle emissions from fossil fuels

Life-cycle emissions from biofuels

At each stage in the distribution chain, carbon dioide is emitted through energy use by extraction, transport, and so forth.

Carbon dioxide emitted will be reabsorbed as the next generation of feedstock is grown.

Figure 2. Life-cycle CO_2 emissions. (Reprinted by permission from Air Transport Action Group, *Beginner's Guide to Aviation Biofuels* [Geneva, Switzerland: Air Transport Action Group, May 2009], 3, http://www.enviro.aero/Content/Upload/File/BeginnersGuide_Biofuels_WebRes.pdf.)

burning of the biofuel. Although biofuels are not "carbon neutral" since it takes energy to run the equipment needed to grow, extract, transport, and process the biomass, the total amount of CO_2 released into the atmosphere by producing and using a biofuel is in theory significantly lower than that released into the atmosphere by a fuel produced from petroleum or other fossil fuels.[28] The alternative fuel we investigated (derived from a CBTL process) does not have the same carbon-neutral potential as one derived entirely from biomass because a large percentage of the CBTL-derived fuel is produced from coal; however, in theory, CBTL-derived jet fuels should affect the environment less than JP-8 because of the percentage of biomass they contain.

The life-cycle stages explored in our analysis included raw material extraction (mining/agriculture), raw material processing (refining/FT), and jet fuel use (burning fuel in flight) (see fig. 1). The transportation of material between these stages and its effects on the environment are captured internally by the EIO-LCA through economic interrelationships and incorporated into the total GWP of the GHG emission outputs at each stage. The authors assume that JP-8 and CBTL jet fuels emit the same total amount of GHGs in the jet-fuel-use LCA stage. According to the Energy Information Administration, the total GWP of the GHGs emitted during the use phase is typically 84 percent of the total GWP of the GHGs emitted during the entire life cycle for kerosene-based jet fuel.[29] We assume that the disposal phase does not exist since aircraft burn the fuel and nothing remains to dispose of after expending the energy source.

We need to make some caveats concerning our hybrid analytical model. The EIO-LCA database we used contained 2002 data, which may not reflect the economy of 2011.[30] Although a number of industries still use the same processes they employed in 2002, many have switched to more efficient ones that change their environmental footprint. For example, coal mining primarily uses the same technology today as it did in 2002, while vehicles such as the new hybrids are more efficient than standard fuel vehicles.[31] The accuracy and completeness of this database are thus uncertain, which translates into uncertainties in the EIO-LCA methodology. Additionally, the FT process to produce synthetic jet fuel was not available in 2002; therefore, the authors estimated the cost of producing CBTL fuels via the FT process to calculate their GWP due to GHGs. Despite these uncertainties in using EIO-LCA to compare JP-8 to CBTL, the process offers decision makers an approximation of the greener jet fuel for the environment.

To use the EIO-LCA model, one must first determine the cost of the resources required for the product, process, or service in the life-cycle stage under assessment. During this process, the EIO-LCA tool applies to the material-extraction phase of both fuels. For the material-processing phase, the EIO-LCA model applies only to the JP-8 jet fuel; the model does not apply to CBTL fuel because the FT synthesis process is not a standard industry in the United States. Therefore, no appropriate industry or sector exists to represent this stage in the EIO-LCA model. Finally, we did not include the jet-fuel-use LCA stage for both fuels because we assumed that the fuels have the same total GWP.

Costs for JP-8 Fuel

The total cost of a typical diesel fuel is the sum of four categories of costs. Using a retail price of $2.80 per gallon in October 2010, one finds that these categories included 17 percent for taxes, 12 percent for distribution and marketing, 6 percent for refining, and 65 percent for crude oil.[32] The authors estimated the cost associated with raw material extraction and processing for JP-8. Since the Air Force spent $6.7 billion on jet fuel in 2008, we estimate that the costs of raw material extraction (the value of the crude oil) and refining were approximately $4.4 billion and $402 million, respectively.[33] The detailed EIO-LCA database sectors that we selected for these costs were "oil and gas extraction" and "petroleum refineries."

Costs for Coal-Biomass-to-Liquid Fuel

The CBTL jet fuel we analyzed consisted of 8 percent (by weight) biomass and 92 percent (by weight) coal. Based on the Air Force's jet fuel use of 2.4 billion gallons in 2008, meeting the service's goal of "acquir[ing] 50% of the Air Force's domestic aviation fuel requirement via an alternative fuel blend" (mentioned above) equates to 600 million gallons of an alternative fuel.[34] Therefore about 550 million gallons of that amount would come from coal, and the remaining 50 million gallons would come from switchgrass. Since it takes about one-half of a short ton of coal to produce a barrel (42 gallons) of diesel fuel and one dry ton of switchgrass to produce one barrel of CBTL fuel, it would take about 6.5 million short tons of coal and 1.2 million dry tons of switchgrass to produce 1.2 billion gallons of jet fuel blend stock.[35] With coal selling for $42 per short ton as of January 2010 and switchgrass selling for $53 per dry ton, the total cost of raw material extraction is $273 million and $64 million, respectively.[36] The detailed EIO-LCA database sectors selected for these costs were "coal mining" and "all other crop farming." As previously mentioned, the EIO-LCA tool does not apply to the refining process; therefore, we obtained the environmental impacts from the Department of Energy.

To determine the environmental impact of each fuel, we summed the results for each life-cycle stage for each fuel. According to the EIO-LCA model results, the GWP for the CBTL fuel was 14 percent less than that for the JP-8 fuel, not considering carbon capture. In other words, the CBTL fuel emits 14 percent less GHGs, so it is greener. However, the Energy Independence Security Act of 2007 (EISA 2007) requires the life-cycle GWP of a prospective alternative jet fuel to be 20 percent less than the GWP of a petroleum-based jet fuel.[37] Since we found the CBTL's GWP to be only 14 percent less than the baseline amount, the CBTL without carbon capture does not qualify as an alternative fuel as defined by EISA 2007.

We also analyzed additional cases involving varying percentages of biomass, with and without carbon capture. Figure 3 presents the results, comparing the percent biomass used in CBTL with the greenness of CBTL compared to that of JP-8. The horizontal line at 20 percent represents the government standard set by EISA 2007. The dashed line shows the LCA results without considering carbon capture sequestration (CCS), while the solid line shows the results when including CCS. The figure shows that, without considering CCS (a more conservative assumption), the minimum amount of biomass to use in making CBTL fuel is 8–10 percent. In all cases, if CCS is considered,

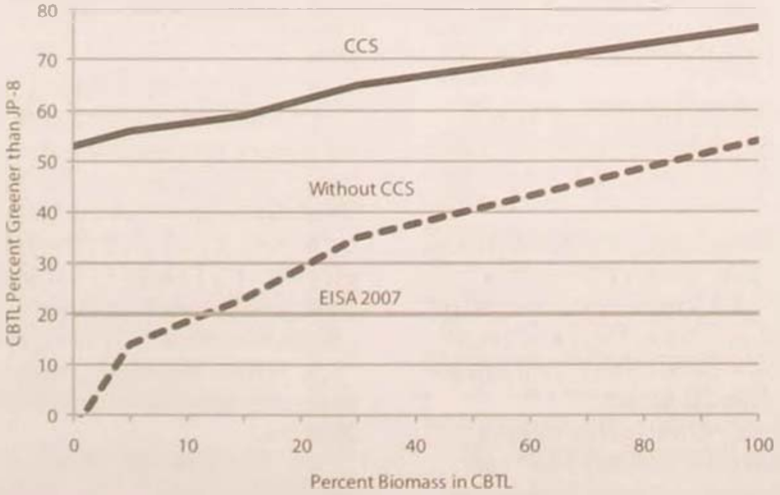


Figure 3. Percent biomass in CBTL versus CBTL percent greener than JP-8

then all CBTL fuels meet the EISA 2007 standard. At lower biomass percentages, the use of CCS significantly improves the greenness of CBTLs compared to that of JP-8.

Conclusion

Alternative fuels give the DOD options for fueling its extensive fleet of vehicles. The Air Force has embraced alternative fuels, which can fulfill the goal of the service's energy initiative (increasing the supply of fuel from domestic sources). However, determining the greenness of a fuel can prove difficult. Air Force decision makers must consider fuels that are comparable in cost and sustainability; furthermore, the fuels must lend themselves to production in significant quantities, have a life-cycle GHG footprint lower than that of petroleum-derived jet fuel (i.e., they are greener), and produce no degradation of flight safety.[38] Two issues arise in implementing an alternative fuel source. First, US regulations such as EISA 2007 demand that an alternative fuel have a total GWP 20 percent less than a baseline. Second, decision makers require an analytic method of evaluating the environmental impact of a fuel's life cycle.

This article demonstrated an analytical method that Air Force leaders can use to determine a fuel's greenness by comparing an alternatively produced jet fuel to a petroleum-derived one. As illustrated in figure 3 (above), the total GWP of all CBTL cases with and without simple CCS is less than the total for JP-8 jet fuel except for the case of 100 percent coal-to-liquid jet fuel without CCS. Therefore, according to an EIO-LCA analysis, the CBTL process produces a greener jet fuel over the entire life cycle. Consequently, we recommend that the Air Force use these alternative fuels as described in its energy strategy.

Air Force and DOD leaders may decide that strategic advantages of a US-made fuel source outweigh the need for an additional LCA. However, at a minimum, the Air Force should support additional field research to improve our understanding of the environmental impact of alternative fuel usage. Moreover, it should investigate the other portions of the supply chain that support aircraft fuels (such as fuel storage) to avoid any potential adverse, unintended consequences of using alternative fuels. ✪

Wright-Patterson AFB, Ohio

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Using Nanotechnology to Detect Nerve Agents

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Dr. Dong Shik Kim
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Nanotechnology has opened a wide range of opportunities having potential impacts in areas as diverse as medicine and consumer products. In collaboration with researchers at the University of Toledo (UT), Air Force Institute of Technology (AFIT) scientists are exploring the possibility of using a nanoscale organic matrix to detect organophosphate (OP) nerve agents. Current techniques for detecting OP compounds are expensive and time consuming. Developing a nanoscale organic matrix sensor would allow for direct, real-time sensing under field conditions. This article describes the science behind such a sensor and its possible applications.

High-performance sensors are needed to protect Soldiers and civilians from attack. At present, doctrine requires Air Force units to resume their primary mission within two hours of a chemical or biological strike.[1] Meeting the two-hour operational goal may mean the difference between defeat and victory. However, OP detection capabilities now in place are limited in sensitivity, time required to operate, and ease of use, making the specified two-hour window difficult to meet.

In the event of a chemical attack, military personnel must have the most sensitive and rapid means available of detecting and quantifying the concentrations of chemical agents. For example, VX, one of the most lethal and persistent nerve agents, causes death in 50 percent of the population at a concentration of approximately 1.2 milligrams per cubic meter (mg/m^3) after a 10-minute exposure.[2] This concentration is about the same as one teaspoon of agent released into a one-meter-high layer of air covering the area of a football field. At this concentration, equipment currently in the inventory can easily detect VX. However, after a three-hour exposure, VX at a concentration of about 0.08 mg/m^3 (15 times lower) will still cause death. Unfortunately, these low concentrations are at or below the detection limits of conventional chemical-warfare-agent equipment. Similarly, 50 percent of the population will experience nonlethal yet mission-inhibiting effects such as pinpointing of the pupils and nausea or vomiting at 0.01 mg/m^3 after a 10-minute exposure.[3] This concentration is equivalent to a teaspoon of agent released into a one-meter-high layer of air covering the area of over 100 football fields. If personnel cannot reliably detect VX contamination at these low concentrations, then mission-critical personnel may become incapacitated, thereby hindering mission accomplishment. Alternatively, as a conservative measure, commanders may order personnel to don individual protective equipment (IPE) when the concentration of a chemical warfare agent is unknown. Although such

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equipment does protect people, it also reduces their mission effectiveness. Therefore, monitoring even trace levels of chemical warfare agents in the environment would allow personnel to remove IPE when appropriate, thereby avoiding the physiological stress of wearing full protective clothing.[4] Furthermore, since civilian populations include children and the elderly, who can be more sensitive to the effects of chemical warfare agents at lower concentrations, a need exists to improve the use of sensors in the event of a terrorist attack on civilians.

Air Force bioenvironmental engineering units currently possess Hazardous Air Pollutants on Site (HAPSITE) systems capable of detecting, identifying, and measuring chemical warfare agents at very low concentrations, enabling personnel to make assessments of the risk of exposure.[5] The HAPSITE uses gas chromatography, which requires collecting and sometimes pretreating a gas or liquid sample before injection into a separation column (fig. 1). After moving through the separation column, the target molecules reach a detector that measures their concentration. The signal generated in the detector is then transformed into a readable electric signal for display. However, weighing approximately 70 pounds, this equipment can be cumbersome to operate, requires regular (weekly) preventive maintenance and use by specially trained personnel, and is quite expensive (over $100,000 per unit).[6] Furthermore, the HAPSITE could take upwards of 30 minutes to run in order to quantify chemical warfare agents at the lowest concentrations—not optimal in a combat environment that demands rapid response. Therefore, improvements in the sensitivity of detection and quantification, speed, and accuracy remain a pressing need.

Nanotechnology offers an approach for improving detection systems. Nanosensors operate at the molecular level, where the reaction between target molecules and sensor elements is direct—almost instantaneous—and by-products of the reaction are transferred to detection units almost instantaneously. Furthermore, nanosensors do not require a separation process to isolate the target molecules. Nanoscale sensor design (fig. 2) uses a sensing element that has a specific affinity for the target molecules. This strong, specific affinity eliminates the need for extra sample preparation, pretreatment, or a separation process. Immobilization and orientation of the sensing elements are precisely engineered so that by-products of the reaction between target molecules and sensing elements transfer to the microelectrode rapidly and accurately. The entire system can be installed in a handheld or dosimeter-type device at a much lower price than for conventional chromatography analyzers. Note, however, that the sensor is chemical specific. Therefore, identification of unknown nerve

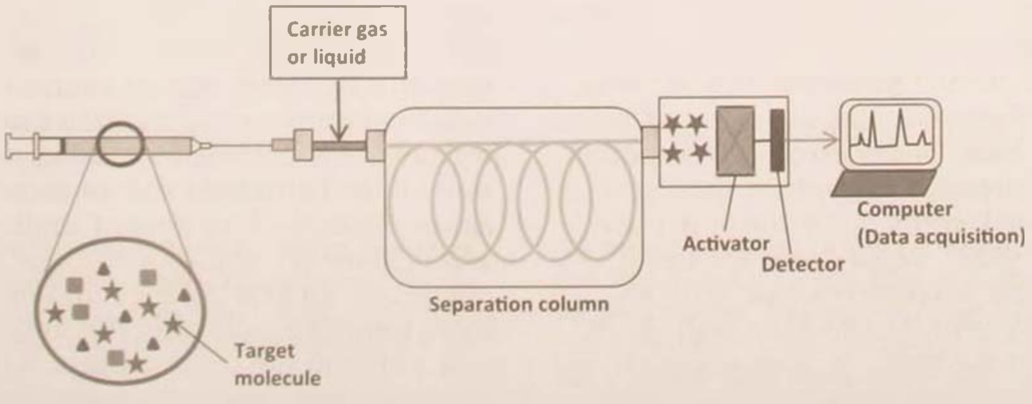

Figure 1. Schematic description of a typical gas chromatography detection system

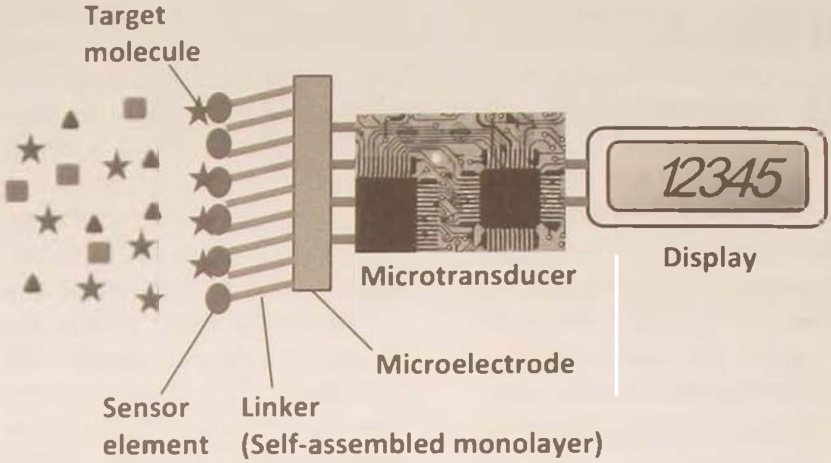

Figure 2. Schematic description of a nanosensor system on a microchip

agents will necessitate integration of several nanosensing matrices into one unit.

Researchers at UT and AFIT are developing an enzyme nanobiosensor for detecting OP compounds such as the nerve gas component dimethylmethylphosphonate (DMMP), used in the synthesis of sarin nerve agent. The sensor is classified as a biosensor because it uses an enzyme to detect the target molecule. DMMP, among the most toxic substances known and a suspected carcinogen, may prove lethal if inhaled, swallowed, or absorbed through the skin. OP compounds incapacitate and kill, primarily by inhibiting an enzyme essential for the functioning of the central nervous system in humans, thus interfering with muscle activity and producing serious symptoms and eventual death.[7]

Effective detection of DMMP involves use of the enzyme organophosphorus hydrolase (OPH) as the sensor element due to its high affinity for DMMP. Since the enzyme is an organic chemical, it may degrade and lose its effectiveness because of a phenomenon called deactivation. Therefore, the enzyme is first placed within a protective peptide nanotube (PNT). Researchers are using PNTs for this purpose because they are simple to synthesize and have high chemical and thermal stability, good conductivity, excellent biocompatibility, and functional flexibility.[8] In preliminary tests, the OPH enzyme within the PNT was four times stabler than free enzymes. An OPH can be attached readily to the inside wall of a PNT, which is then attached to a specially prepared linker called a self-assembled monolayer to form a sensor matrix on an electrode (see fig. 2). OPH-based biosensors are effective for directly monitoring and measuring various OPs ranging from OP-based pesticides and insecticides to chemical warfare agents like sarin.[9] The detection limit for the biosensor is in the range of 0.005–0.01 mg/m^3 of DMMP in air.[10] Therefore, the biosensor—two to four times more sensitive than conventional detection equipment—can detect extremely low concentrations that result in nonlethal but significant effects on humans. Moreover, the biosensor produces results three times faster than conventional detectors. In addition, the biosensor's reduced size and increased sensitivity could make it well suited for installation on a remotely piloted aircraft—a very significant military application since these aircraft are becoming increasingly important on the battlefield and for reconnaissance missions. This kind of application would allow for remote sensing of airborne chemicals, facilitating safer and more efficient sampling. Although this application exists only in the concept stage, it has great potential. Because the nanosensor under development is compound-specific, it would respond only to the target molecule and would not likely be subject to interference from other compounds.

Along with the PNTs used to protect the OPH enzyme, research is also concentrating on the self-assembled monolayer linker, which plays an important role in the nanosensor matrix because it controls the rate of electron transfer from the OPH to the sensor. Researchers are investigating various combinations of linker molecules and sizes in order to optimize sensor performance. AFIT and UT investigators are testing the electron transfer rate and precision of the signal for different combinations of short and long linkers. On the one hand, short linkers speed up that rate (therefore, they are sensitive), but the capacitance of the short-linker layer is not low enough to suppress noise coming from other electrolytes (therefore, short linkers are not precise). On the other hand, long linkers reduce noise (therefore, they are precise), but electron transfer is slow. Consequently, optimum sensitivity and precision performance will emerge from a proper combination of the short- and long-linker molecules.

As stated above, two critical problems—enzyme deactivation and reduced sensitivity/precision—arise in enzyme sensors. The UT and AFIT researchers are addressing these problems by (1) using PNTs to protect the enzyme and increase service life, and (2) specially designing linker molecules to maximize both sensitivity and precision.

Nanotechnology has great potential for making handheld, fast, and accurate OP sensors. Fabrication of a small yet very sensitive and accurate sensor for installation on a remotely piloted aircraft could have significant military value. Similarly, handheld sensors have notable, worthwhile applications for combat and homeland defense. Fast, accurate, and inexpensive detectors could be deployed to give population centers and military installations early warning of a chemical strike. Following an attack, a reconnaissance team may need to sample several base sites before determining the proper protection requirement for personnel. Even if biosensors reduce the amount of sampling time typical of conventional methods by just a few minutes, the cumulative time savings could be substantial. Furthermore, improved detection sensitivity would inspire more confidence during the determination of risk in areas with low concentrations of chemical contamination. If personnel can safely reduce the time spent wearing IPE following an attack, then mission effectiveness would increase. Similarly, if nonlethal but mission-impairing concentrations of OP agents exist, commanders could direct personnel to don IPE. This biosensor technology offers a more cost-effective and improved chemical detection method for meeting current and future threats. Additionally, PNT is a novel material that enhances OPH enzyme activity and shelf life essential to nanoscale biosensors. Clearly, the Air Force would do well to support development and commercialization of such devices. ✪

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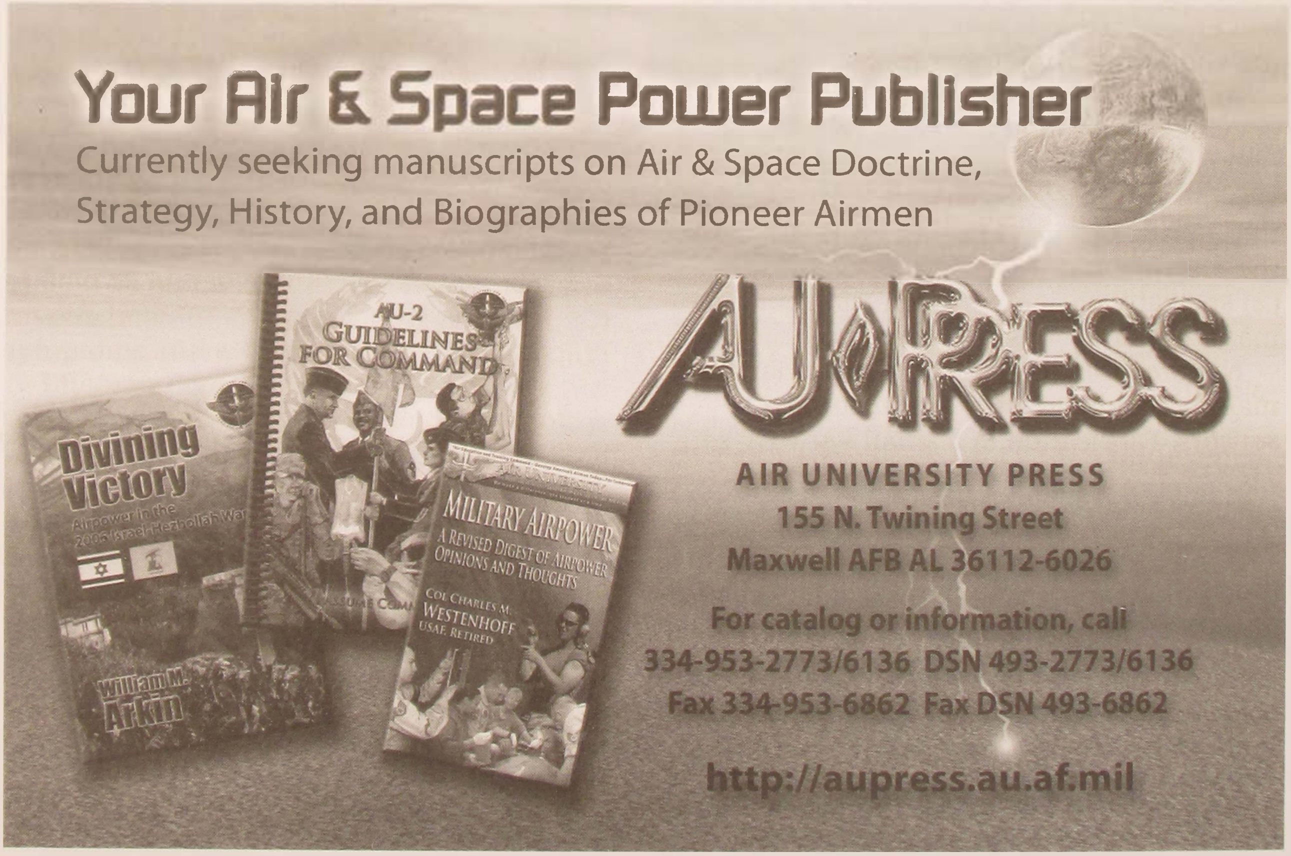

X-HALE

Designing the Atmospheric Surveillance Platforms of the Future

Lt Col Christopher M. Shearer, USAF*

Imagine the benefits that battlefield commanders or intelligence analysts could derive from an airborne surveillance platform that would carry a 500-pound payload, operate above the range of small-arms fire, remain on station for weeks or even years, cost much less than a satellite, and relocate around the globe to a new region of interest within a couple of weeks. Realizing this concept, known as a high-altitude, long-endurance (HALE) aircraft, is a 10-to-15-year goal of researchers at the Air Force Institute of Technology (AFIT). In order to reach this goal, those researchers are following a developmental path similar to the one the Wright brothers used over a century ago by gathering new test data and building theoretical formulations for this aircraft. The brothers' discovery that the existing aeronautical data of the day was inaccurate proved key to their success. Indeed, Wilbur Wright even wrote that "having set out with absolute faith in the existing scientific data, we were driven to doubt one thing after another, until finally, after two years of experiment, we cast it all aside, and decided to rely entirely upon our own investigations."[1]

The air and space community experienced a dramatic reminder of the importance of developing accurate aerodynamic data and computer software on 26 June 2003. On that date, the National Aeronautics and Space Administration's (NASA) Helios aircraft, a uniquely flexible HALE design intended to cruise up to an altitude of 100,000 feet, became unstable during a test flight and crashed due to excessive wing deformation, followed by uncontrolled flight and catastrophic failure of upper-wing surfaces. Accident investigators concluded that the root cause of the accident was a "lack of adequate [aerodynamic] analysis methods [which] led to an inaccurate risk assessment of the effects of configuration changes leading to an inappropriate decision to fly an aircraft."[2] Even though modern fifth-generation fighter aircraft are designed with state-of-the-art aeronautical tools, the latter fail at designing very flexible HALE aircraft that fly at less than 80 miles per hour. Furthermore current tools fail to predict the stability and control of these aircraft.

The Helios accident highlighted the limitations of our understanding and of the analytical tools (computer software) necessary for designing HALE aircraft such as the Helios, which have the potential to offer immunity from most ground threats while providing low-cost surveillance. Following the Helios accident, NASA's primary recommendation called for the development of "more advanced, multidisciplinary (structures, aeroelastic, aerodynamics, atmospheric, materials, propulsion, controls, etc.) '*time-domain*' analysis *methods* appropriate to highly flexible, 'morphing' vehicles" (emphasis in original).[3]

Despite the lack of fundamental aerodynamic knowledge and analytical tools

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(particularly computer software) necessary to understand the aerodynamic behavior of these vehicles, aircraft designers are still striving to develop aircraft that incorporate the latest sensor technology. However, most of these designs continue to have critical constraints in the areas of mission duration, the payload's electrical power supply, and payload weight. To fully exploit the potential of sensor technology, we need a long-term surveillance platform.

Researchers at AFIT have been collaborating with the Defense Advanced Research Projects Agency (DARPA) since 2008 to develop a HALE aircraft capable of remaining airborne continuously for five years. The Vulture program has the potential to combine the best aspects of aircraft station keeping and low-cost relocation with the persistence and high-ground advantage of a satellite system.

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Due to mission requirements, HALE aircraft are characterized by high-aspect-ratio wings and slender fuselages, resulting in very flexible vehicles. These geometric constraints make the aircraft susceptible to large, dynamic wing deformations at low frequencies. Such deformations can adversely affect the vehicle's flight characteristics, as demonstrated during the Helios flight tests.[4] Despite that accident, development of DARPA's Vulture program, developmental designs of other civilian HALE aircraft, and recent analytical work reveal a severe shortage of experimental test data.[5] These data are critical to further advance an understanding of the flight dynamics and control of HALE aircraft and to validate recent progress in software and aerodynamics.[6]

An Experimental High-Altitude, Long-Endurance Aircraft

AFIT began a research effort in 2007 to locate existing, available data for validating the software and aerodynamic theory for HALE aircraft. That effort ended when a DARPA-sponsored meeting of experts from academe, the Department of Defense (including the author), NASA, and industry confirmed the suspicion that no complete set of available data existed for such validation research.[7] Interestingly enough, NASA's Helios aircraft could have supplied this information had political and programmatic obstacles not prevented installing instruments on the aircraft to collect it.

Because of the lack of available data, AFIT began a second research effort, utilizing the unique expertise of researchers at the University of Michigan. On 27 August 2008, AFIT formed a partnership with the university's Aerospace Engineering Department to develop an experimental high-altitude, long-endurance (X-HALE) remotely piloted aircraft supported by the Air Force Research Laboratory's (AFRL) Air Vehicles Directorate and directed by AFIT. The partnership has designed a HALE aircraft using tools developed by AFIT, AFRL, and the University of Michigan, producing two different design configurations (see figure) with certain design characteristics (see table). If the response to tests of the aircraft's initial configuration (having a six-meter wingspan) does not provide the requisite flight dynamic features (coupled wing flexibility with aircraft lateral and longitudinal control), then testing will move to the eight-meter concept.[8]

The first X-HALE flight test is scheduled for late spring or summer 2011 at Camp Atterbury, Indiana. For these tests, the University of Michigan will provide expertise in handling the aircraft; AFIT, flight-test expertise and program management; and AFRL, funding and program oversight. The tests seek to validate HALE aircraft design tools by employing accumulated flight-test data to build and fly the X-HALEs successfully. For the first of two series of X-HALE flight tests, the aircraft will carry a limited set of instrumentation to reduce programmatic risk. Upon successful completion of this series of tests, researchers will build a second vehicle with more extensive instrumenta-

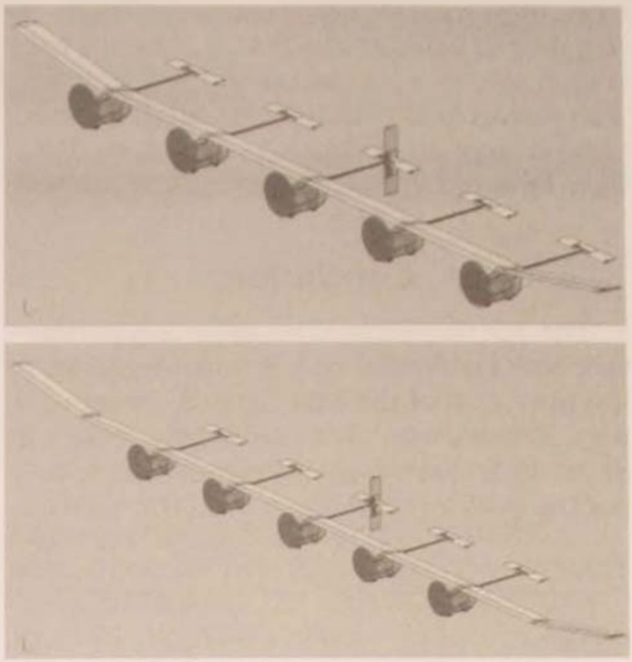

Figure. X-HALE six- (above) and eight-meter (below) wingspan designs

Table. Characteristics of X-HALE remotely piloted aircraft

Wingspan	6 meters (m) or 8 m
Chord	0.2 m
Planform Area	1.2 square meters (m^2) or 1.6 m^2
Aspect Ratio	30 or 40
Length	0.96 m
Propeller Diameter	0.3 m
Gross Takeoff Weight	11 or 12 kilograms (kg)
Power/Weight	30 watts/kg
Airspeed	12–18 m/second
Maximum Range	3 kilometers
Endurance	45 minutes

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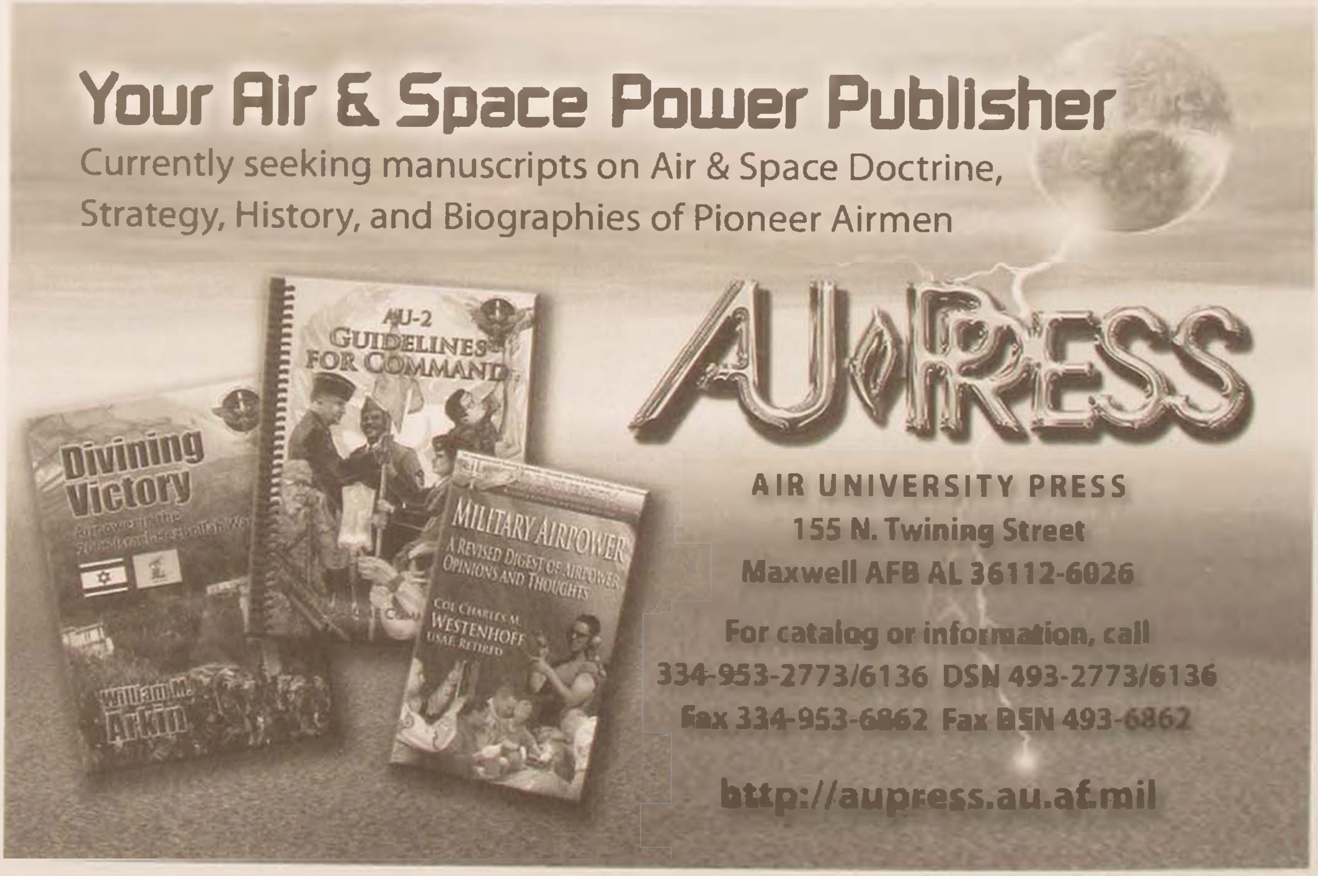

X-HALE

Designing the Atmospheric Surveillance Platforms of the Future

Lt Col Christopher M. Shearer, USAF*

Imagine the benefits that battlefield commanders or intelligence analysts could derive from an airborne surveillance platform that would carry a 500-pound payload, operate above the range of small-arms fire, remain on station for weeks or even years, cost much less than a satellite, and relocate around the globe to a new region of interest within a couple of weeks. Realizing this concept, known as a high-altitude, long-endurance (HALE) aircraft, is a 10-to-15-year goal of researchers at the Air Force Institute of Technology (AFIT). In order to reach this goal, those researchers are following a developmental path similar to the one the Wright brothers used over a century ago by gathering new test data and building theoretical formulations for this aircraft. The brothers' discovery that the existing aeronautical data of the day was inaccurate proved key to their success. Indeed, Wilbur Wright even wrote that "having set out with absolute faith in the existing scientific data, we were driven to doubt one thing after another, until finally, after two years of experiment, we cast it all aside, and decided to rely entirely upon our own investigations."[1]

The air and space community experienced a dramatic reminder of the importance of developing accurate aerodynamic data and computer software on 26 June 2003. On that date, the National Aeronautics and Space Administration's (NASA) Helios aircraft, a uniquely flexible HALE design intended to cruise up to an altitude of 100,000 feet, became unstable during a test flight and crashed due to excessive wing deformation, followed by uncontrolled flight and catastrophic failure of upper-wing surfaces. Accident investigators concluded that the root cause of the accident was a "lack of adequate [aerodynamic] analysis methods [which] led to an inaccurate risk assessment of the effects of configuration changes leading to an inappropriate decision to fly an aircraft."[2] Even though modern fifth-generation fighter aircraft are designed with state-of-the-art aeronautical tools, the latter fail at designing very flexible HALE aircraft that fly at less than 80 miles per hour. Furthermore current tools fail to predict the stability and control of these aircraft.

The Helios accident highlighted the limitations of our understanding and of the analytical tools (computer software) necessary for designing HALE aircraft such as the Helios, which have the potential to offer immunity from most ground threats while providing low-cost surveillance. Following the Helios accident, NASA's primary recommendation called for the development of "more advanced, multidisciplinary (structures, aeroelastic, aerodynamics, atmospheric, materials, propulsion, controls, etc.) '*time-domain*' analysis *methods* appropriate to highly flexible, 'morphing' vehicles" (emphasis in original).[3]

Despite the lack of fundamental aerodynamic knowledge and analytical tools

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(particularly computer software) necessary to understand the aerodynamic behavior of these vehicles, aircraft designers are still striving to develop aircraft that incorporate the latest sensor technology. However, most of these designs continue to have critical constraints in the areas of mission duration, the payload's electrical power supply, and payload weight. To fully exploit the potential of sensor technology, we need a long-term surveillance platform.

Researchers at AFIT have been collaborating with the Defense Advanced Research Projects Agency (DARPA) since 2008 to develop a HALE aircraft capable of remaining airborne continuously for five years. The Vulture program has the potential to combine the best aspects of aircraft station keeping and low-cost relocation with the persistence and high-ground advantage of a satellite system.

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Due to mission requirements, HALE aircraft are characterized by high-aspect-ratio wings and slender fuselages, resulting in very flexible vehicles. These geometric constraints make the aircraft susceptible to large, dynamic wing deformations at low frequencies. Such deformations can adversely affect the vehicle's flight characteristics, as demonstrated during the Helios flight tests.[4] Despite that accident, development of DARPA's Vulture program, developmental designs of other civilian HALE aircraft, and recent analytical work reveal a severe shortage of experimental test data.[5] These data are critical to further advance an understanding of the flight dynamics and control of HALE aircraft and to validate recent progress in software and aerodynamics.[6]

An Experimental High-Altitude, Long-Endurance Aircraft

AFIT began a research effort in 2007 to locate existing, available data for validating the software and aerodynamic theory for HALE aircraft. That effort ended when a DARPA-sponsored meeting of experts from academe, the Department of Defense (including the author), NASA, and industry confirmed the suspicion that no complete set of available data existed for such validation research.[7] Interestingly enough, NASA's Helios aircraft could have supplied this information had political and programmatic obstacles not prevented installing instruments on the aircraft to collect it.

Because of the lack of available data, AFIT began a second research effort, utilizing the unique expertise of researchers at the University of Michigan. On 27 August 2008, AFIT formed a partnership with the university's Aerospace Engineering Department to develop an experimental high-altitude, long-endurance (X-HALE) remotely piloted aircraft supported by the Air Force Research Laboratory's (AFRL) Air Vehicles Directorate and directed by AFIT. The partnership has designed a HALE aircraft using tools developed by AFIT, AFRL, and the University of Michigan, producing two different design configurations (see figure) with certain design characteristics (see table). If the response to tests of the aircraft's initial configuration (having a six-meter wingspan) does not provide the requisite flight dynamic features (coupled wing flexibility with aircraft lateral and longitudinal control), then testing will move to the eight-meter concept.[8]

The first X-HALE flight test is scheduled for late spring or summer 2011 at Camp Atterbury, Indiana. For these tests, the University of Michigan will provide expertise in handling the aircraft; AFIT, flight-test expertise and program management; and AFRL, funding and program oversight. The tests seek to validate HALE aircraft design tools by employing accumulated flight-test data to build and fly the X-HALEs successfully. For the first of two series of X-HALE flight tests, the aircraft will carry a limited set of instrumentation to reduce programmatic risk. Upon successful completion of this series of tests, researchers will build a second vehicle with more extensive instrumenta-

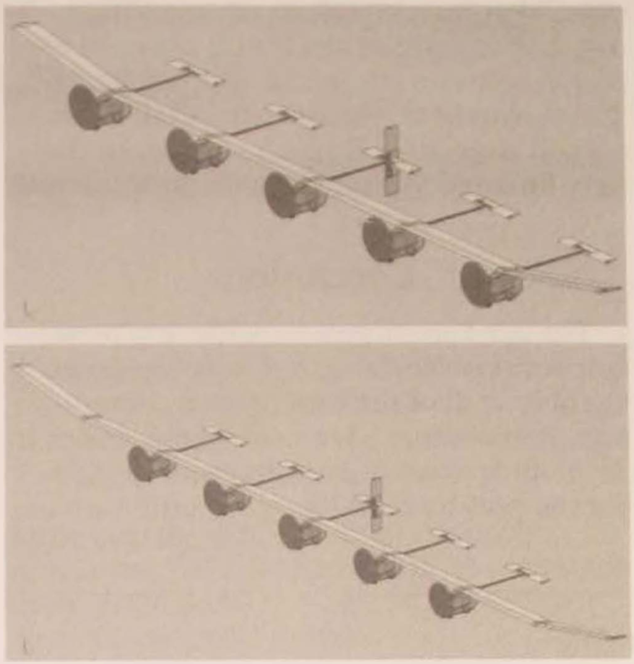

Figure. X-HALE six- (above) and eight-meter (below) wingspan designs

Table. Characteristics of X-HALE remotely piloted aircraft

Wingspan	6 meters (m) or 8 m
Chord	0.2 m
Planform Area	1.2 square meters (m^2) or 1.6 m^2
Aspect Ratio	30 or 40
Length	0.96 m
Propeller Diameter	0.3 m
Gross Takeoff Weight	11 or 12 kilograms (kg)
Power/Weight	30 watts/kg
Airspeed	12–18 m/second
Maximum Range	3 kilometers
Endurance	45 minutes

tion and flight-test objectives to meet the primary research goal of collecting flight-test data to validate the HALE aircraft's research software and aerodynamic theory. The researchers plan to share all data with several large air and space companies that have followed this project with great interest.

Conclusion

The Air Force's goal of achieving persistent aerial surveillance has long represented the holy grail of the intelligence community. Researchers have made great strides in developing aircraft platforms and sensors, but the proliferation of asymmetric warfare means that the United States desperately needs aircraft that can loiter over a target of interest for weeks or years. AFIT's researchers, along with its strategic partners, are making great progress in offering these tools to the war fighter. Currently, the way forward involves combining the high ground of satellites with the navigational flexibility of aircraft. The X-HALE program will supply the test data and the validated design tools that AFIT and industry researchers need to design an aircraft to meet our war fighters' need for persistent aerial surveillance. ✪

Wright-Patterson AFB, Ohio

Notes

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8. "Coupled wing flexibility with aircraft lateral and longitudinal control" results from the inherent flexibility of HALE aircraft wings. In response to an aileron or roll input, the outer portion of the wing initially deforms. The movement of the rest of the airplane lags behind this initial movement of the wing. This reaction resembles the way an ocean wave first forms, yet the resulting motion of the water at the shoreline lags behind the initial movement of the wave. The lag in movement of the aircraft due to an aileron input creates additional problems with stability and control. In most aircraft, the wing is so stiff that aileron inputs cause the entire aircraft to begin to roll almost instantly.

Aerospike Rockets for Increased Space Launch Capability

Lt Col Carl Hartsfield, PhD, USAF
Lt Col Richard D. Branam, PhD, USAF
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Mr. Joseph Simmons*

The US Department of Defense (DOD) increasingly depends on space assets for everyday operations. Precision navigation; communications; and intelligence, surveillance, and reconnaissance satellites are highly leveraged space assets. The launch vehicles that place these satellites in orbit are a major limitation of current space systems. If higher-performing launch vehicles were available, many satellites could accommodate additional capabilities, whether in terms of more sensor channels, types of payloads, electrical power, or propellant for orbital maneuvering and station keeping. Space assets are typically designed to conform to a particular launch vehicle's limitations (e.g., engineers might design a satellite to be carried by a Delta IV-2 medium launch vehicle). Essentially, this choice of vehicle fixes the maximum mass of the satellite and, thus, its capabilities. If a launcher capable of placing more mass in the desired orbit were available at similar cost, the satellite's design could allow for additional capability. Furthermore, some payloads are too heavy for present-day launch vehicles to place into a particular orbit. A better-performing launcher would enable us to put those payloads into the desired orbits, permitting new missions and capabilities. To overcome these limitations, the Air Force Institute of Technology (AFIT) conducts ongoing research into rocket propulsion technologies to improve space launch performance.

Two significant problems hinder space launch today: launch performance and cost. Performance involves the payload mass that a vehicle can place into a given orbit, whether low Earth orbit (LEO) or geosynchronous Earth orbit (GEO). The Delta IV Heavy, capable of delivering 50,655 pounds into LEO or 14,491 pounds into GEO, represents the current limit on DOD launch capacity.[1] Increasing this capacity necessitates either larger launch vehicles or higher performance from existing ones. Larger vehicles drive a series of additional expenses, including more propellant, expanded launch facilities, and bigger processing facilities. Although improved vehicles entail new development costs, they may be compatible with existing facilities.

Launching any medium or heavy vehicle costs hundreds of millions of dollars. One estimate puts total launch costs of a Delta IV Heavy launcher at $350 million; other estimates are somewhat lower.[2] A

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study by the RAND Corporation in 2006 places launch costs for DOD payloads at $100–$200 million.[3] The true expenditure of each launch is probably closer to the higher values at our current launch rates; however, more launches would push the cost per launch towards the lower values. Regardless, launch expenses are immense. Using the capacities and costs above, we can determine that the price of lifting payload to GEO amounts to $7,000–$25,000 per pound, and to LEO $2,000–$7,000 per pound. A Delta IV Heavy weighs about 1.6 million pounds at liftoff. Approximately 85 percent (1.3 million pounds) is propellant (fuel and oxidizer). If we assume an expenditure of approximately $5 per pound for both hydrogen and oxygen (averaged among hydrogen sources), then we spend about $6.5 million for propellant.[4] Because the price of fuel depends upon the cost of natural gas (the most convenient source of hydrogen), any estimates are quite volatile. However, even substantial changes in the cost of hydrogen will not have a great effect on overall expenses since the current propellant makes up less than 5 percent of the overall launch outlay; this simple analysis also applies to the cost of oxidizer. Thus, two large categories comprise about 95 percent of expenditures: launch base operations and launch vehicle materials and production. Clearly, reducing launch expenses entails (1) bringing down labor costs associated with the launch base by using simpler processes and designing for maintainability and higher reliability, and (2) lessening material and labor expenditures associated with the vehicle by making components reusable where possible, simplifying assembly of the launch vehicle, avoiding exotic materials, simplifying the geometry of component parts to reduce difficult machining steps, and so forth. AFIT's research in aerospike rocket engines, sponsored by the Air Force Research Laboratory Propulsion Directorate, seeks to increase vehicle performance and decrease launch costs.

Current Research: Improved Upper-Stage Engine

Current research at AFIT involves designing and optimizing a cryogenic liquid hydrogen / liquid oxygen upper-stage engine. This new engine design, known as the dual-expander aerospike nozzle (DEAN), will serve as an orbit-transfer engine to propel a payload from LEO to GEO. The DEAN differs from other cryogenic upper-stage engines in two ways. First, it utilizes separate expander cycles for the oxidizer and fuel. Second, unlike bell-nozzle engines, it employs an aerospike (radial inflow plug) nozzle (fig. 1).

In a typical engine-expander cycle, the fuel alone regeneratively cools the combustion chamber and nozzle.[5] Regardless of engine design, the chamber walls require some form of cooling since combustion temperatures typically reach about 5,000° F (stainless steel melts at about 2,550° F).[6] Energy transferred to the fuel during regenerative cooling acts as the sole driver for the turbo pumps that inject the fuel into the combustion chamber. Since the energy available to drive the pumps is limited to whatever heat transfer occurred during cooling, expander-cycle engines typically have relatively low chamber pressures. Higher combustion-chamber pressures would improve engine performance in three basic ways: First, greater pressures lead to more efficient combustion and enhanced energy release from the fuel. Second, higher pressures improve the potential specific impulse produced by the engine—improving thrust and performance.[7] Finally, elevated chamber pressures lead to smaller chamber volumes and potentially less engine weight, although this advantage is partly offset by the increased material thickness necessary to withstand the greater pressure.

The RL-10, the standard evolved expendable launch vehicle's upper-stage engine, utilizes the expander cycle. This cycle has the advantage of simplicity. Specifically, it does not require the preburners or gas gen-

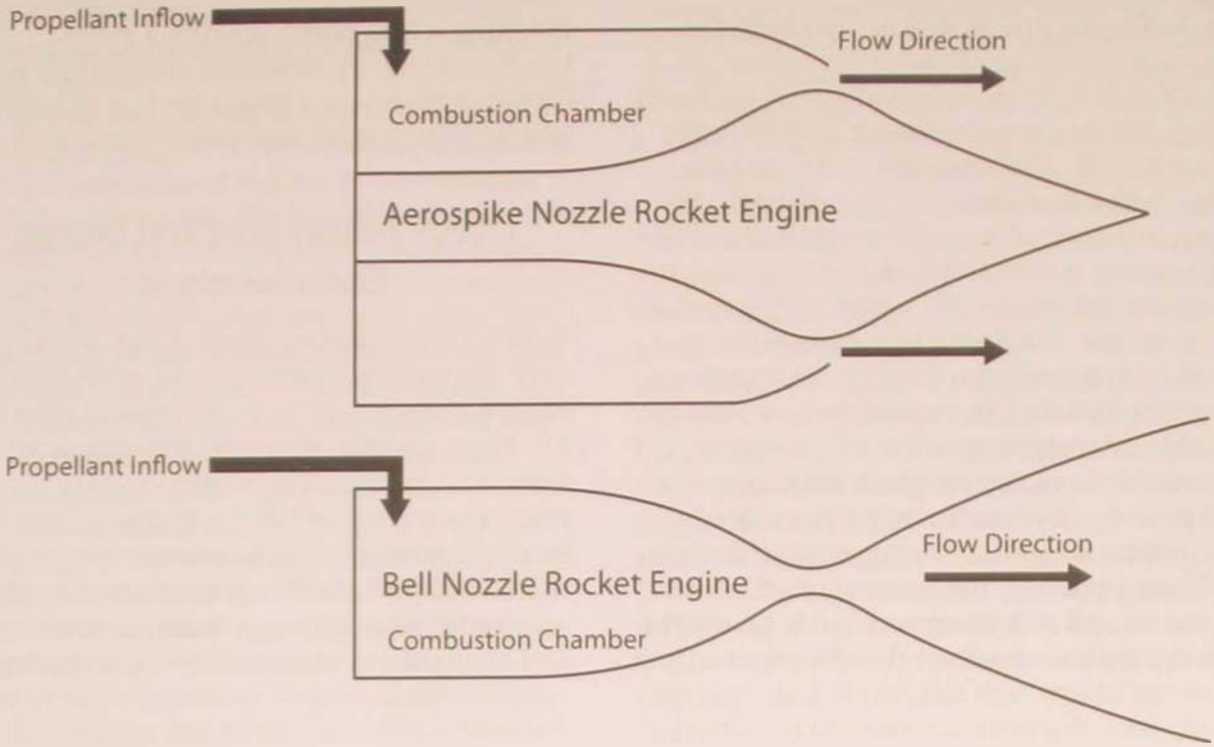

Figure 1. Geometry of aerospike and bell-nozzle rocket engines

erators needed by some other liquid-fuel cycles; it permits the use of lightweight turbo pumps because the working fluids in the turbines remain relatively cool (approximately 80–440° F rather than 2,200–3,100° F seen in other designs), allowing designers to choose lighter materials. Moreover, the cycle facilitates smooth ignition and start-up because it reaches full thrust with a much more gradual ramp-up, whereas staged combustion and gas-generator cycles tend to yield full thrust very rapidly.[8]

Although the DEAN uses the expander cycle, it is unique in that the oxidizer and fuel pass through separate expander cycles. The oxidizer cycle drives the oxidizer turbo pumps, and the fuel cycle drives the fuel turbo pumps. Since the pump and turbine sides of turbo pumps must share a common shaft, seals separate the high-pressure (pump) side and the low-pressure (turbine) side. A conventional expander-cycle engine has one turbine, driven by the fuel and two pumps on the single shaft—one for fuel and one for oxidizer. Although seals separate fuel in the turbine, fuel in the pump, and oxidizer in the pump, they have a potentially disastrous failure mode. If a seal between the high-pressure fuel and high-pressure oxidizer fails, the mixture of fuel and oxidizer can produce an explosion that would destroy the engine, launch vehicle, and payload. Separate fuel and oxidizer cycles have the advantage of physically separating the oxidizer and fuel until injection into the combustion chamber, thus eliminating the risk of explosions caused by failure of the interpropellant seals. Since the latter scenario represents one of the more catastrophic failure modes in traditional expander-cycle engines, the DEAN's dual-expander design can improve operational safety and mission assurance.[9]

The DEAN also uses a radial inflow plug nozzle primarily to enable the dual-expander cycle but also to allow a shorter, lighter engine. The direct performance advantages of the aerospike nozzle are not exploited in the upper-stage application for which the DEAN is designed. In low ambient pressure, which applies to upper-stage engines operating at high altitudes, aerospike nozzles behave like conventional bell nozzles. For these missions, the rocket engine requires a high expansion ratio for the nozzle, which increases the length and weight of the engine. For example, the Delta IV's second-stage RL-10B2 engine has a deployable nozzle extension to attain the required expansion ratio; the extendable portion of the nozzle, almost 6.5 feet long, weighs a little more than 203 pounds (an additional 86 pounds of equipment supports deployment).[10] In low ambient pressure, the aerospike offers savings in weight and size compared to an equivalent expansion-ratio bell nozzle, especially if the spike is truncated or chopped short of reaching a fine point, leaving a planar, blunt end (fig. 2). Research shows only negligible performance losses for the aerospike nozzle due to moderate spike truncation.[11]

DEAN Advantages and Design Considerations

The DEAN design offers many benefits over the currently operational orbit-transfer RL-10B2 engine, all of which would save the Air Force money, improve mission assurance, and help assure access to space for years to come. The DEAN engine, designed for high performance, saves engine weight and fuel, lends itself to manufacturing that uses today's technology, features robustness and tolerance of extensive ground testing,

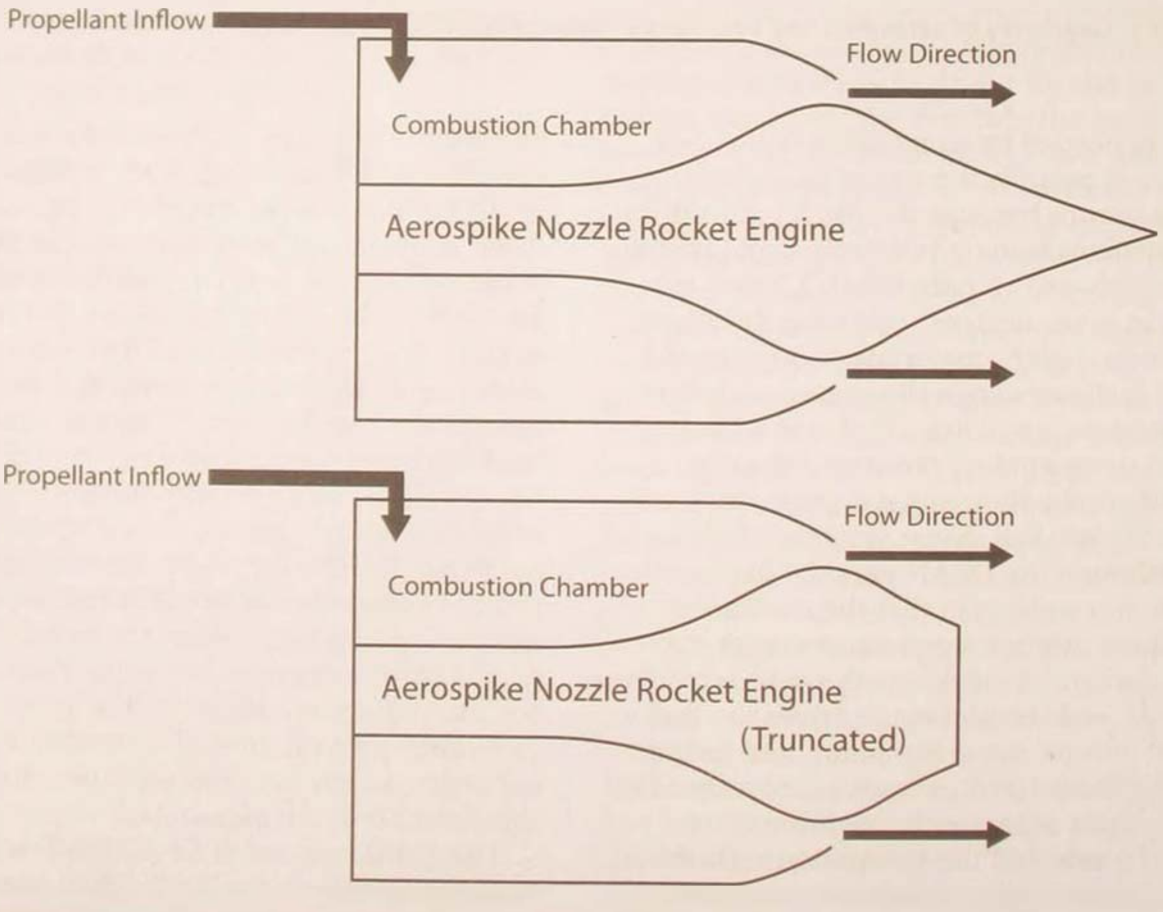

Figure 2. Geometry of truncated and nontruncated aerospike engines

and incorporates features that eliminate some catastrophic failure modes for upper-stage engines.

Any design strives to improve upon previous designs. Delta IV's RL-10B2 represents the current state of the art in upper-stage rocket engines, but the DEAN is designed to outperform that technology. When completed, AFIT's current models indicate that the DEAN will provide just over twice the thrust and weigh approximately 20 percent less than the RL-10B2.[12] Using a higher propellant-mixture ratio (i.e., less fuel and more oxidizer), the DEAN will operate leaner, demand less fuel, and thus decrease the money spent on fuel slightly since liquid oxygen is somewhat cheaper than liquid hydrogen. Furthermore, AFIT performance calculations indicate that matching or improving the specific impulse of the RL-10B2 results in a minimum stage-weight savings of 105 pounds due to the reduced estimated weight of the DEAN.[13] Any improvements in specific impulse would enable additional weight savings for the launch vehicle as a whole. The higher the specific impulse, the less propellant needed to realize the desired thrust. This weight savings permits an increase in payload weight, which may include the addition of new capabilities to the satellite being launched. Because of the costliness of launches, a savings in weight equates directly to one in expenditures; therefore, a 105-pound weight savings can save the government on the order of $1 million (at about $10,000 per pound, based on mean values of the costs discussed earlier).[14]

Utilizing an aerospike upper stage also brings indirect benefits to the first-stage booster. The interstage (part of the first stage) encapsulates the upper stage to protect its components during atmospheric travel. This component is dead weight in the sense that, though necessary for the mission, its weight decreases the amount of payload, engine, and propellant the vehicle can carry, so engineers seek to make the interstage as small and light as possible. Because the aerospike design is shorter than a bell nozzle and can produce the same amount of thrust, especially when the aerospike is truncated, the interstage structure can be made smaller and lighter compared to the interstage for the RL-10B2. Doing so equates to indirect benefits to the booster stage in weight, size, and performance.

The considerations discussed above influence the DEAN's design. Its combustion chamber and nozzle will use standard metals and ceramics compatible with the propellants. Furthermore, the engine will use current off-the-shelf turbo pumps and plumbing. Combined, these two features will improve the design's near-term manufacturability.

The DEAN's designers wish to make the engine reusable and robust enough to withstand extended ground testing prior to launch. Taking a conservative approach, AFIT engineers determined a maximum wall temperature for both the combustion chamber and aerospike that would prevent degradation of material strength. Our modeling rejected designs unable to maintain combustion chamber and aerospike temperatures below the limits established for the materials simulated.

Future Work: High-Performance Booster Engine

The next step in aerospike rocket research at AFIT calls for applying the aerospike nozzle to first-stage (booster) engines. The nozzle offers the significant performance advantage of operating nearly optimally at all altitudes below its design altitude, thanks to a capability known as altitude compensation. Conversely, a conventional bell-nozzle engine, such as the space shuttle's main engine, is designed for optimal operation at a single design altitude, suffering performance losses at all other altitudes. The aerospike design has significant performance advantages during operation through the atmosphere. In rocket engines, the nozzle expansion ratio is a key to maximizing engine performance. A high expansion ratio leads to low exhaust pressure, increasing the conversion of potential output (represented by the chamber temperature and pressure) to thrust output (exhaust momentum and pressure). Exhaust pressures in excess of the ambient atmospheric pressure for the flight altitude generate some thrust, but a larger expansion ratio could convert that extra pressure into increased momentum and more thrust than the pressure alone can provide. Therefore, for all rockets, the largest expansion ratio nozzle possible represents a performance advantage. However, for conventional bell-nozzle rocket engines, the nozzle's size has limitations. If the exhaust pressure is less than about 25–40 percent of the ambient pressure, the exhaust flow will separate within the nozzle, forming shock waves and causing large thrust losses. To avoid this condition, engineers generally design rocket engines to operate with exit pressures no lower than about 60 percent of the ambient pressure, providing some margin of safety.[15] This sets a practical limit for bell-nozzle expansion ratio, based on the lowest altitude at which the rocket is expected to operate. Normally, the engine designer sets the design altitude to about 12,000 feet, where the atmospheric pressure is about 62 percent of sea-level pressure.[16] Setting the design altitude any higher creates the potential for separated flow within the nozzle and greatly reduced thrust. Therefore, at all altitudes above that, the rocket produces substantially less thrust than it could ideally (see fig. 3).

The aerospike nozzle does not suffer from this disadvantage. Increased ambient pressure effectively reduces the expansion ratio to a point where the exhaust pressure matches the ambient pressure. In this way, the aerospike nozzle compensates for altitude up to its design altitude, represented by its physical expansion ratio. Above this altitude, the aerospike nozzle acts much like a bell nozzle, with the excess exhaust pressure generating some extra thrust as the rocket climbs above its design altitude. Since no fluid-dynamic reason exists for limiting the nozzle expansion ratio, the practical limit to the aerospike's ratio comes from the fact that the outside diameter of the engine effectively sets that ratio; thus, an extremely large expansion ratio requires a very large-diameter engine, adding considerable weight. The challenge lies in balancing the increased performance with the increased weight to find an optimal point for the launch vehicle.

This near-ideal performance becomes especially important during the low-altitude boost phase of the rocket flight. With no other performance changes to the launch vehicle, AFIT's initial modeling studies indicate that changing the first-stage engine to aerospike nozzle engines could produce an approximately 6 percent increase in the mass that the vehicle can lift to GEO. The difference in performance, calculated for identical chamber pressures and mixture ratios, could see improvement with changes to these and other parameters. AFIT's research aims at identifying an optimal engine design (or a set of optimal designs) that may not share operating conditions with current lift engines such as the RS-68 used in the Delta IV launcher. Performance alterations such as increasing the combustion-chamber pressure can significantly enhance specific impulse and payload capacity. If the aerospike operates at double the RS-68's chamber pressure, the improvement in mean specific impulse also doubles, as does the increase in payload capacity to GEO.

We have modeled the performance of a conventional bell-nozzle rocket, an aerospike-nozzle rocket, and an ideal rocket with an infinitely adjustable area-ratio nozzle and no thrust losses due to friction or other factors (fig. 3). The conventional rocket, built around a 12,000-foot design altitude to allow separation-free operation at sea level for launch, assumes a 95-percent-efficient nozzle design to account for friction and other loss effects. Note that the specific impulse remains below that of the aerospike at all altitudes except 12,000 feet. Furthermore, the shape of the curve for the conventional rocket does not track the ideal nozzle, indicating less-than-optimum performance at all altitudes. The aerospike rocket features

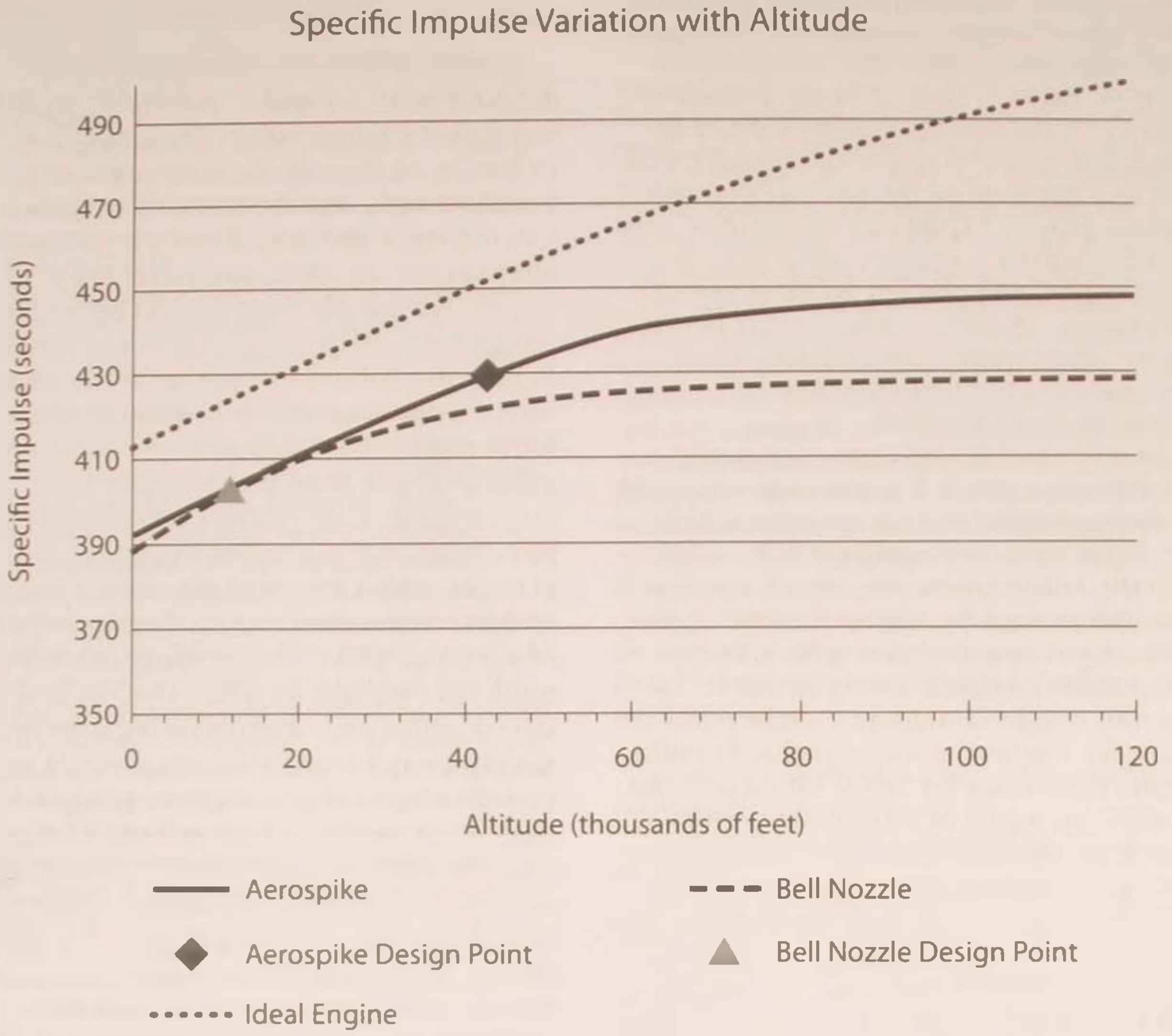

Figure 3. Performance advantage of aerospike engines in the atmosphere

chamber conditions identical to those of the conventional rocket but has a design altitude of 43,000 feet since that setting produced an engine slightly smaller than the diameter of a Delta IV first stage. The figure shows that the aerospike's specific-impulse curve runs parallel to the ideal curve, up to 43,000 feet. The aerospike curve assumes a 95-percent-efficient nozzle to account for losses, thus falling below the ideal. Notably, although the aerospike nozzle has a diameter of nearly 13 feet to reach exhaust-gas expansion appropriate for pressure conditions at 43,000 feet, the adjustable nozzle must expand from about six feet in diameter at sea level to almost 52 feet in diameter at 118,000 feet. To continue this performance until the rocket reaches near vacuum at 262,000 feet, the nozzle would have to expand to 672 feet in diameter—clearly impractical. Long before this point, the engine would become too heavy to lift itself, much less any fuel or payload.

Through a boost of slightly more than 3 percent in mean specific impulse on the first stage with an aerospike, without accounting for any weight savings by using the DEAN engine on the upper stage(s), current AFIT modeling indicates the possibility of realizing a 6 percent gain in maximum payload to GEO. Improving from a Delta IV payload limit of 14,491 pounds to GEO to 15,355 pounds would enable a significant increase in spacecraft capability as well as a decrease in the payload's launch cost per pound. Doubling the chamber pressure produces a 6 percent rise in specific impulse and a 13 percent increase in GEO payload—to 16,437 pounds. Similar performance improvements would also result from utilizing the first-stage aerospike engine to attain LEO orbits.

As with the DEAN's upper-stage engine, the aerospike-nozzle booster engines would be more compact than conventional bell-nozzle engines. Replacing the bell nozzle with the radial-inflow plug nozzle can expand the maximum diameter of the engine, but using a truncated aerospike allows a much shorter engine. Doing so can translate into weight savings and might make the aerospike engines more adaptable to multiengine operations for larger lift capabilities.

AFIT set a goal of improving performance and producing a more compact engine while maintaining operability with key subsystems such as propellant pumps and materials. By ensuring that the performance required of the turbo pumps lies within that demonstrated in testing for realistic launch conditions (the National Aeronautics and Space Administration refers to this as technology readiness level six, a system adopted by the DOD acquisition community), AFIT can reduce the risks associated with depending on outside developments.[17] By restricting material choices to conventional metals and ceramics, the AFIT design team can avoid needing any breakthroughs in materials. However, the team will take advantage of any such advancements in scientific material to further improve the aerospike engine's performance in the future.

Conclusion

As an Air Force, we find ourselves at a decision point for space operations. Most of our rocket engines reflect decades-old technology in all aspects of their construction. Costs are high, and the vehicles are generally not reusable, even if we recover them after launch. At AFIT, our rocket team thinks that the Air Force can do better. The reduced weight of the DEAN would result in incremental improvements to launch capacity without extensive reworking of the lower stages. The increased specific impulse available from the aerospike first-stage engine could produce a significant improvement in the satellite weight we can place in orbit. Currently, the overall weight of the launch vehicle limits the capabilities of our space platforms. In many cases, we must omit adjunct payloads that could offer new or enhanced capabilities because we simply cannot launch the extra weight or provide electrical power (more power implies more weight in solar panels) to support the additional equipment. Enhancing our launch capability helps solve this problem. Moreover, designing engines for reliability, maintainability, and operability from the start will improve launch costs and launch rates. At AFIT we believe that the Air Force needs a push in the direction of building an updated launcher since we know that developing the technology will take many years, and building a new launcher many more years. As an air and space force, we cannot wait for obsolescence of current platforms to start development of a follow-on space launch platform. We must start now, and AFIT research is pointing the way. ✪

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Notes

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A Taskable Space Vehicle

Realizing Cost Savings by Combining Orbital and Suborbital Flight

Capt Thomas C. Co, USAF
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The use of space gives the United States distinct advantages in any battlefield environment, but the high cost of space operations increasingly jeopardizes those advantages. Although the United States pioneered much of the current space technology, declining budgets for space research, development, and operations leave our legacy systems vulnerable to adversaries around the world. Other nations formerly incapable of space exploitation are quickly learning to counter US space technologies at surprisingly low costs. In order to reduce the expense of deploying and maintaining a robust space capability, the Department of Defense (DOD) must change the status quo in space operations or risk losing its dominance. The US Strategic Command, National Aeronautics and Space Administration, Defense Advanced Research Projects Agency, and Air Force recognize the problem of sustaining the United States' edge in space despite declining budgets. Tasked with bridging the gap between available resources and operational needs, the Operationally Responsive Space (ORS) Office envisions significant progress, but we should expand its vision. This article proposes a phased approach that will multiply the cost savings of the ORS program (hereafter referred to simply as ORS) and increase US space capabilities; this approach harnesses the potential of the orbital and suborbital flight of space planes and existing satellites for repeatedly maneuvering and performing multiple missions.

Established in 2007 as a joint initiative of several agencies within the DOD, the ORS Office seeks to develop low-cost access to space via missions responsive to war fighters' needs. Access to space is not cheap; vehicle development and launch comprise the largest part of space expenditures. ORS strives to drive down the costs of both those components simultaneously so that we can prepare and launch a space vehicle within weeks at a fraction of the current outlay (for as little as a penny for every dollar now spent on comparable missions).[1] At present, however, ORS focuses only on quickly preparing vehicles and launching them cheaply—it does not envision maneuverable space vehicles that could change their orbits to perform more than one mission during their service lives. According to Dr. James Wertz, an ORS proponent, "[Responsive space] cannot be achieved with already on-orbit assets. [It is] like hoping the bad guy will step into the path of a bullet which has already been shot."[2] Using the same satellite for multiple missions by employing nontraditional, orbital-change tech-

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niques can enhance responsiveness to war fighters' needs while reducing program costs even further.

Implementation of this new responsive-orbit approach should proceed in four phases. The first phase will show that some currently operational satellites can modify their orbits significantly in an efficient manner simply by changing the concept of operations (CONOPS). The hardware for this technology already exists and is well tested and understood. Such a system needs an electric propulsion system (gridded ion thruster or Hall Effect thruster) and a small satellite platform (weighing 500–1,000 kilograms).[3] The second phase will apply moderate amounts of aerodynamic drag to the satellite, such as those experienced in the outer atmosphere for altitudes ranging between 150 and 700 kilometers (km) above the earth's surface (known as the thermosphere).[4] In addition to a new CONOPS, electric propulsion, and a small platform, the third phase will demand a vehicle capable of manipulating aerodynamic forces (similar to the space shuttle and X-37). We find these three hardware components employed individually in spacecraft today. Therefore we need only a new CONOPS and the right combination of vehicle characteristics to turn an on-orbit satellite into a maneuverable space asset. The fourth and final phase will combine maneuverability with ORS concepts under development. Evolution of the first phase is under way, showing the potential of the responsive-orbit concept. Future phases will progress as follows.

Operationally Responsive Space

The United States' present use of space drives a DOD space program that typically costs billions of dollars. Traditional space missions are strategic, durable (designed for 10- to 20-year life cycles), inflexible, expensive ($100 million–$2 billion), highly capable, complicated, and hard to replace.[5] These characteristics are interrelated. Due to the considerable expense of launching spacecraft, designers make their systems extremely capable and reliable. Those traits come at a premium cost and produce long life cycles. Highly capable, reliable, and long-lasting systems must have redundancies for all components critical to their operation (almost the entire system)—and those redundancies add weight, which leads to greater launch expenditures. Clearly, this self-sustaining cycle creates ever-growing, supercapable spacecraft that cost billions of dollars and take a decade to build. This paradigm has become the defining characteristic of space culture. Today's requirements for rapid reconstitution and assets responsive to unplanned threats and disasters necessitate additional space-acquisition models.

Current space missions often fall short of meeting the needs of war fighters. The systems demand long development times to mature and integrate the necessary technologies. By the time a system is ready to deploy, many of its electronic components are no longer state of the art, so engineers must design new ones. The DOD cannot keep up with the demands of military operations.[6] Users often wait several years beyond the originally planned delivery date before they finally receive a new asset whose intended purpose may have already changed. During the planning for Operation Desert Storm in September 1990, planners realized that existing satellite communications (SATCOM) capacity would not be sufficient to support the war effort; consequently, they urgently attempted to launch an additional Defense Satellite Communications System III spacecraft. The mission finally launched on 11 February 1992, missing the war by more than a year.[7] Designers produced the follow-on to that spacecraft, the Wideband Global SATCOM, as a commercial off-the-shelf system because of advertised time savings in the acquisition schedule. When its development began in 2001, the launch was scheduled for the fourth quarter of 2003, yet the satellite did not attain operational orbit until 2008 (after launch on 7 October 2007)—five years behind schedule.[8] This delay caused critical communication shortages in the Pacific Command and Central Command theaters, resulting in up to 80 percent reliance on commercial assets at inflated costs to taxpayers.

ORS seeks a paradigm shift in space operations. In contrast to the latest methodology, ORS missions are designed to be tactical, short (intended for a one-year life cycle), flexible (adaptable to mission need, timeline, and geographic region), cheap (less than $20 million), specialized (spacecraft provide a specific function and work with other spacecraft to realize an objective, making the overall system less vulnerable to an attack), technologically simple, and immediately replaceable.[9] ORS emphasizes smaller satellites and launch vehicles; rapid, on-demand deployment; and quick availability of capabilities to users. Concepts under development will continue to rely on traditional, Keplerian orbits, meaning that each launched asset serves only a single purpose.[10] Even a cursory comparison of a traditional mission and ORS shows that the latter is everything the former is not.

The ORS approach marks a significant shift in the US space culture. Stakeholders generally agree on the desirability of reducing mission cost and elevating responsiveness to user needs, but fulfilling those goals is difficult, requiring persistence and willingness to change existing hardware, command and control, and testing norms. Hopefully, policy planners will acknowledge the benefits of transforming this culture and embrace new business rules, allowing rapid changes to give us the flexibility to meet user needs quicker and more efficiently.

ORS could offer even greater benefits if it included development of a maneuverable satellite, such as a small one in the 500-kilogram weight class, which can carry sufficient fuel on board to perform multiple maneuvers.[11] That is, the vehicle could perform an orbital change after completing one mission, thereby permitting retasking to carry out a new one. Assuming that the desired orbital changes were small, the satellite could maneuver 15 times or more.[12] One maneuver would reduce the number of launches by 50 percent—three maneuvers, 75 percent. Regardless of the cost savings in hardware and testing that ORS might realize, launches will remain expensive, especially if we must launch a new satellite for each tasking. Therefore, a maneuverable satellite that we could retask on orbit multiple times could prove far less costly than the ORS version.

Meeting User Needs with a Maneuverable Asset

ORS optimistically presents a single low-cost vehicle launched on demand and to the proper orbit within hours of tasking. This long-term vision of ORS has a target date of 2020. Assuming that such a vehicle exists and that the launch capability and ground control segment are in place, the perennial shortage of available assets to meet operational user needs would expend any on-hand capability as quickly as it could be produced, thereby precluding a truly responsive system. Responsiveness is not limited to the space segment; quick launches can also improve the timeliness of meeting a new user need. Rapidly launching augmentation or replenishment spacecraft can prove essential to maintaining a specific capability. At present, spacecraft production follows a launch-on-schedule concept, but responsive vehicles must be prepared for launch on demand. An effective shift to the latter approach would require maintaining an inventory of war-reserve materiel, spacecraft, and associated launch vehicles at the launch sites.[13]

The ORS concept relies on the ability to launch rapidly from an available inventory to respond to developing crises. It might necessitate launching one satellite and positioning it to monitor a tsunami-devastated area in the Pacific one day and launching another to gather intelligence about a peasant uprising in Central Asia the next day. This capability requires having readily available spares prepared at a moment's notice for launch and operation. However, for the foreseeable future, operational needs will continue to far outpace the rate at which we can field new assets to meet those needs. As demonstrated by the previously discussed SATCOM scenarios, military capacity quickly diminishes as a consequence of supporting newly operational terrestrial and aerial systems that demand substantial bandwidth to transmit data between forward-deployed forces and command centers. In order to build up a responsive capacity (with available inventory), we need a different approach.

Complementing the ORS design with the ability of the space vehicle to maneuver via nontraditional (or novel) orbits would reduce the pressure of a high operations tempo and lower the necessary capacity. Maneuverability would enable a single satellite launched into low Earth orbit to change its orbital plane sufficiently in a timely manner to respond to multiple world events or user requirements. In doing so, the satellite's on-orbit life span might decrease to less than the ORS program's current one-year standard, depending on how many different taskings the asset fulfills. Enabling a single vehicle to meet multiple user demands could greatly lessen the need for repeated launches and thereby reduce cost by millions of dollars per vehicle.

Specifically, these proposed novel orbits would leverage aerodynamic forces of the earth's atmosphere to change orbital parameters. Using simple technology developed during the days of Gemini, Mercury, and Apollo, we can design a space vehicle to reenter the atmosphere, using lift and drag to change orbit by altering its flight path, velocity, and altitude.[14] In essence, the orbital space vehicle becomes akin to a suborbital spacecraft, behaving like an aircraft while inside the atmosphere. Based on multiple reentry profiles simulated using the equations of motion provided by Lt Col Kerry Hicks, a vehicle designed with sufficient lift capability can perform aircraft-like maneuvers such as climbing, diving, and rolling.[15] This non-Keplerian part of the flight profile not only would enable a change in the orbit (the ground track required to fulfill a new operational objective) but also would add a degree of uncertainty for adversaries interested in tracking this vehicle. Thus, an adversary might be caught by surprise, having little or no prior warning of the vehicle coming overhead. The depth to which the satellite penetrates the atmosphere determines the control authority of the mechanisms put in place to modify orbital parameters. A deep atmospheric penetration can drastically change the orbit in ways that even high-thrust, liquid-propellant rocket engines cannot because of the prohibitive amount of fuel expended by those engines.[16]

A vehicle capable of entering and exiting the atmosphere unharmed by g-forces and heating due to atmospheric friction would certainly require some design changes. Since ORS strives to change the culture of space operations and architecture completely, it presents the perfect opportunity to take the idea further by considering novel approaches to increase flexibility and provide greater benefit to the effort with relatively simple modifications. The effects, controls, benefits, and dangers of reentry have been well known since the early days of manned space flight. By carefully selecting features of a vehicle's design, we can greatly enhance its lift capability and, therefore, the aerodynamic control authority to modify its orbit. Doing so would expand the flight envelope and increase operational flexibility.

The maneuverable vehicle concept, to a much lesser extent for altitudes above 150 km, also applies to current operational satellites not designed with ORS capabilities. Atmospheric-drag forces play a role in a satellite's orbit at or below an altitude of 700 km. The space shuttle and the International Space Station experience these forces constantly and must counter them to prevent orbital decay. The technology that allows satellites to maneuver is available and in use, but the CONOPS must change (phase one). Low-thrust electric engines enable satellites already in orbit to perform slow, precise, and highly efficient station-keeping maneuvers. The current CONOPS calls for the spacecraft to arrive at its orbital state and maintain orbit, almost exclusively, for the life of the vehicle. Because most spacecraft are designed in this manner, we don't give much thought to powered flight and its potential. When necessary, these engines can move large satellites into orbits to serve different terrestrial theaters, in the case of a geosynchronous system, or change the time a satellite arrives over a target (time over target [TOT]) for a system in low Earth orbit.[17] To harvest this potential, the CONOPS must proceed from the assumption that these spacecraft do not necessarily have to operate within the orbit into which they were first launched. Additionally, when we take into consideration the potential of the upper atmosphere to change a vehicle's orbit (even small drag forces can induce a noticeable change), a system already on orbit can maneuver significantly to change its TOT or geographical location even without modifying vehicle characteristics (phase two).

Concept Design and Results

A small orbital change can affect the terrestrial ground track of a satellite. An asset without ORS hardware that continuously thrusts with an electric engine over a seven-day period can sufficiently change its velocity within the same orbital plane to produce a 24-hour TOT change by modifying the ground track.[18] The ground-track alteration is proportional to the lead time provided to adjust the orbit. In simple terms, the more time available to implement a TOT change, the greater the magnitude of the potential change. Phases one and two of the research program can realize this result when an existing system's CONOPS is modified to allow maneuvers that change the TOT. Yet, the response time cannot compare to the potential response time claimed by ORS systems under development. Ultimately, an ORS asset will be capable of reaching any location on the earth within 45 minutes of launch and only nine hours following initial tasking.[19] However, this ORS goal has not yet become reality. A current asset that can maneuver in orbit using electric propulsion but not enter the atmosphere (i.e., remain above an altitude of 122 km) can reach any location on the earth at any specified TOT in seven days. In comparison, simulations show that a maneuverable asset designed with aerodynamic characteristics capable of leveraging atmospheric forces and out-of-plane maneuvers could reduce the time required to attain the desired orbit by about 75 percent (i.e., from seven days to approximately two), as discussed in phase three. With a little ingenuity, we can combine the atmospheric maneuvers with an ORS satellite to provide an inexpensive, highly effective system capable of quickly responding to the threats that the United States faces today.

An ORS asset is designed as a small, light satellite capable of maintaining attitude (pointing) and location (station keeping). To make it maneuverable (phase four), we could design the satellite with both a small impulsive-thrust (rocket) engine and a highly efficient electric-thrust capability (such as a Hall Effect thruster). Impulsive thrust enables rapid yet small changes in orbit, and continuous electric thrust builds up the energy to reach a stable parking orbit enabling repetition of the process. The design concept would involve launching such a satellite into a specific orbital plane to meet the needs of the initial tasking. After completing its first mission, the vehicle would impulsively modify its orbit slightly to cause its perigee (point in the orbit closest to the earth's surface) to enter or "dip" into the atmosphere where the satellite could use aerodynamic forces to change its orbital plane to meet requirements of the next tasking. Each time the vehicle performs such a maneuver, it loses energy. Simulations show that when the satellite's energy level can barely sustain orbital flight, the continuous electric-thrust system will efficiently raise that level enough to keep the vehicle in orbit. This process can be repeated until the satellite runs out of fuel for its propulsion system. A space plane equipped with the two types of engines described above (rocket and electric) could respond to multiple user taskings by using present-day technology—yet the knowledge of how to execute these maneuvers effectively remains quite limited. This design concept would strive to increase the number of taskings the system could fulfill by a factor of six compared to traditional assets in low Earth orbit equipped solely with chemical propulsion. (The efficiency [or gas mileage] of low-thrust electric engines is five to six times greater than that of high-thrust engines.) Such a space plane could fulfill 15 or more taskings, thereby completing 15 ORS missions with a single launch and reducing the advertised mission cost significantly.

Conclusion

The current space culture of fielding large, expensive, and capable satellite systems is not sustainable; it can neither satisfy the operational needs of US war fighters nor keep up with threats posed by other spacefaring nations. Just as conventional warfare must adapt to today's counterinsurgency demands, so must conventional space culture adapt to today's space environment. New initiatives such as ORS and the research discussed in this article seek to do just that.

We should take a phased approach to expanding the current ORS concept. In phase one, a new CONOPS built around a different paradigm for an existing on-orbit asset can provide a test bed for demonstrating the feasibility of attaining significant TOT change by using electric propulsion while remaining outside the atmosphere. The necessary technology is already in use, well tested, and understood. The fact that this phase does not require developing any new equipment would keep costs low. The second phase will enable greater flexibility and increased responsiveness to war fighters' needs by incorporating aerodynamic forces in orbits as low as 122 km to open opportunities previously thought impossible due to vehicle and fuel constraints. The third phase will involve a new vehicle designed to enter the atmosphere, perform the desired orbital change, and climb back into space. The technology to create vehicle characteristics best suited to take advantage of lift and drag forces also exists and has undergone much study. Yet, because the countless possibilities for changing a satellite's ground track to support multiple missions as proposed remain poorly understood, we need to conduct more research. This phase offers great potential for effecting large-scale orbital changes at very low fuel costs, increasing the life span of a satellite (when compared to inducing the same amount of change using traditional chemical propulsion), and enabling it to fulfill five to six times as many taskings as current operational satellites not designed to maneuver significantly. The final phase would expand the scope of ORS to include maneuverability. Allowing such effective, low-cost satellites to perform multiple taskings during their operational life spans would reduce the number of launches and give us sufficient capability to make ORS a truly responsive system.

The inevitable paradigm shift in the US space program has begun. Our future conventional space operations must include small, cheap, responsive, and maneuverable assets that we can develop and launch in months rather than decades. ✪

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Notes

1. James R. Wertz, *Responsive Space Mission Analysis and Design* (El Segundo, CA: Microcosm Press, 2007), 4. (This is a manual that accompanies a course on the subject taught by Dr. Wertz.) We compare the responsive mission's cost of $20 million for launch, spacecraft, payload, and one year of operations to the $2 billion spent on traditional programs (before including operation costs).

2. Ibid., 5.

3. A Hall Effect thruster is a type of ion propulsion engine in which an electric field accelerates the propellant. Hall thrusters trap electrons in a magnetic field and then use them to ionize propellant, efficiently accelerate the ions to produce thrust, and neutralize the ions in the plume. In a Hall thruster, an electron plasma at the open end of the thruster, rather than a grid in a standard ion thruster, provides the attractive negative charge. See *Wikipedia: The Free Encyclopedia*, s.v. "Hall effect thruster," http://en.wikipedia.org/wiki/Hall_effect_thruster; and "Hall Effect Thruster Systems," Busek, accessed 2 March 2011, http://www.busek.com/hall effect.html.

4. The boundary between the earth's atmosphere and outer space is not definite. Satellites are affected by atmospheric drag below an altitude of 700 km above the earth's surface. Atmospheric reentry forces become significant at an altitude of 120 km. Current satellites are not designed to withstand such forces.

5. Wertz, *Responsive Space Mission Analysis*, 7.

6. In a series of briefings and meetings during 2007–9, joint wideband working groups discussed the limited capacity of military satellite communications provided by DOD systems and ways of using them to meet military needs. Military systems such as Global Hawk, Predator, and Blue Force Tracking require high-capacity, flexible, and readily available satellite bandwidth that the then-current satellite constellation could not provide. Of growing concern was the DOD's 80 percent reliance on commercial assets. The working groups met quarterly in various locations, including California, Colorado, and Florida. See also Greg Berlocher, "Military Continues to Influence Commercial Operators," *Satellite Today*, 1 September 2008, http://www.satellitetoday.com/military/milsatcom/Military-Continues-To-Influence-Commercial-Operators_24295.html.

7. David N. Spires, *Beyond Horizons: A Half Century of Air Force Space Leadership*, rev. ed. (Peterson AFB, CO: Air Force Space Command in association with Air University Press, 1998), 268.

8. "Wideband Gapfiller System," GobalSecurity.org, 10 April 2005, http://www.globalsecurity.org/space/systems/wgs-schedule.htm. The Wideband Gapfiller System was later (about 2007) renamed the Wideband Global SATCOM.

9. Wertz, *Responsive Space Mission Analysis*, 7–9.

10. "Keplerian" refers to the orbit of a satellite around another body governed by the force of gravity and in the absence of atmospheric drag or propulsion (thrusters).

11. Robert Newberry, "Powered Spaceflight for Responsive Space Systems," *High Frontier* 1, no. 4 (2005): 48.

12. Ibid.

13. Les Doggrell, "Operationally Responsive Space: A Vision for the Future of Military Space," *Air and Space Power Journal* 20, no. 2 (Summer 2006): 49.

14. Lt Col Kerry D. Hicks, *Introduction to Astrodynamic Reentry*, AFIT/EN/TR-09-03 (Wright-Patterson AFB, OH: Graduate School of Engineering and Management, 9 September 2009), 239–41.

15. Ibid.

16. "Mars Reconnaissance Orbiter Successfully Concludes Aerobraking," National Aeronautics and Space Administration, 30 August 2006, http://www.nasa.gov/mission_pages/MRO/news/mrof-20060830.html.

17. In 2008 the WGS-1 satellite moved from its test latitude of 122.8 degrees West to 180 degrees West while it was in geosynchronous orbit. The spacecraft executed this phasing maneuver solely by using Xenon Ion Propulsion System thrusters (a type of electric propulsion). For a discussion of TOT change for satellites in low Earth orbit, see Newberry, "Powered Spaceflight," 46–49.

18. Ibid., 48.

19. Wertz, *Responsive Space Mission Analysis*, 9.

Centralized Execution, Decentralized Chaos

How the Air Force Is Poised to Lose a Cyber War

1st Lt John Cobb, USAF*

> *One victory [Operation Desert Storm] has swept all problems under the rug—the US's unchallenged lead in modern weaponry and technology has concealed the fact that their organization and strategy are obsolete, having failed to keep up with their technology.*
>
> —Qiao Liang and Wang Xiangsui, *Unrestricted Warfare*

In the current state of cyber warfare, massive centralized networks are at best fragile and often indefensible.[1] The Air Force's network operations (AFNETOPS) paradigm relies on centralized control of the service's cyberspace; although arguably adequate for maintenance and counterintelligence in "cyber peacetime," it could fail spectacularly if ever tested by a serious cyber attack.

At present, the Air Force relies on a handful of units from the 67th Network Warfare Wing (67 NWW) to handle most aspects of network defense.[2] Primarily brought on by reductions in manpower, this consolidation also came about because of the perceived benefits accrued from establishing unity of command across Air Force cyberspace as well as reducing time-consuming training on network attack and defense tactics, techniques, and procedures. However, in seeking unity of command, the Air Force has almost completely abandoned decentralized execution, leaving its cyberspace vulnerable to a variety of attacks that could isolate base networks from the central network units. Compounding this problem is the fact that most Airmen remain unaware of these vulnerabilities, blindly assuming that enemy cyber attacks will never affect their own mission area. The current AFNETOPS paradigm must give way to a more effective model of network defense. Specifically, the service should take two steps to mitigate the risks of network failure and cross-domain mission failure: (1) cyber operators at the base level must be capable of running their networks and responding to attacks independently of higher-level network units, and (2) Air Force wings need to conduct exercises in which they operate under network isolation, degradation, and outage scenarios.

AFNETOPS includes units responsible for network operations and defense. Twenty-Fourth Air Force handles most aspects of Air Force cyberspace, including nearly all network administration. Within the Twenty-Fourth, the 67 NWW is responsible for most of the service's network defense. Within that wing, key network defense units include the integrated network operations and security centers (INOSC), the Air Force computer emergency re-

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sponse team (AFCERT), the 624th Operations Center, and the 26th Network Operations Squadron. Specifically, the two INOSCs have purview over geographic regions (INOSC East and INOSC West); they configure and operate core services across the base networks in their domain, responsible for most base boundary protection and network security devices (the INOSC runs most network-defense software tools and devices even though they might be physically present at the local base). AFCERT experts "diagnose and treat" viruses and other malware in network emergencies. The 624th Operations Center maintains situational awareness of Air Force cyberspace (including all major network defense issues) for Twenty-Fourth Air Force and other relevant commanders. Finally, the 26th Network Operations Squadron has network-wide oversight and security responsibilities. For example, if base X is attacked by a virus, the INOSC will close down some of the network "entrances and exits" (ports on the firewall) and try to repair any damage; AFCERT will help identify the attack and provide countermeasures; and the 624th Operations Center will coordinate and update commanders on the situation.

Most core network services across the entire Air Force are controlled by these centralized network-operations facilities. Although base-level technicians can control many routine functions such as modifying accounts or adding new machines to the network, only the off-site 67 NWW personnel can deal with major issues and changes because base-level administrator accounts are not configured to allow local technicians to modify core services or servers.[3] Since 67 NWW detachments typically reside at only one base per major command, they rely on functioning links between bases to carry out their mission.[4] In the latest construct, base-level network technicians are somewhat analogous to gas station attendants who can wash and refuel cars but lack the equipment to perform major repairs. Applying this centralized on-call approach to network defense assumes that repair teams can reach the least accessible station to help a customer whose "vehicle" has been damaged by attackers. Additionally, this construct leaves distant stations underprepared when attackers target access roads, preventing repair teams from arriving to help the stranded customer.

When the Air Force's network infrastructure is not under attack, centralized network service causes some frustration but works reasonably well (and, arguably, saves money and manpower compared to possible alternatives). However, in the face of a serious cyber attack, this model will break down. The AFNETOPS construct is the epitome of centralized execution, with attendant operational weaknesses such as unresponsiveness to local commanders, delays in approving and implementing changes, and difficulty adapting standardized equipment and practices to unique locations. Worse, it leaves base networks paralyzed if they become isolated from higher-tier units (or, specifically, higher-level administrator accounts).

How likely is such isolation? In cyber warfare, it is virtually inevitable. The Air Force leases from private telecommunication companies most of the "circuits" that connect bases, and these circuits are vulnerable to distributed denial of service (DDoS) attacks from hostile botnets. (The network equivalent of radio jamming, botnets are collections of thousands to millions of hijacked computers that hackers use to attack a target simultaneously.)[5] Nor are these leased lines the only weakness—DDoS attacks can also target the firewalls and routers where Air Force networks connect to the outside world. As demonstrated by the Internet isolation of Estonia in 2007, technology does not always allow a quick response to major DDoS attacks against the long-haul links between physical locations (especially at key bottlenecks such as transoceanic cables).[6] To be fair, defenses against DDoS attacks exist (often variations on blocking traffic from parts of the Internet or the entire Internet), but they are not foolproof.[7] A capable cyber foe will not limit his attacks to a mere isolated portion of otherwise functional base networks.

DDoS attacks represent only one method of undermining a base network; the Air Force's network hierarchy is also vulnerable to simpler cyber attacks. An enemy could easily target our vulnerabilities and thereby degrade networks—either in preparation for a DDoS attack or in lieu of one. If a foe can infect a handful of computers with viruses—even simple, crude ones—he can cripple a network just by overloading it with more traffic than the network can handle. (This sort of denial of service differs from a DDoS, in which the overload originates outside the victim network and usually targets boundary devices connecting the victim network to the Internet.) This type of denial-of-service attack, usually involving phishing techniques to implant the viruses, requires some skill to evade network defenses and is difficult to perform successfully if all computers on the network are receiving correct updates and patches.[8] Unfortunately, both state and criminal hackers quite commonly have the skill to launch denial-of-service attacks, and most Air Force networks (including those maintained by the author) include machines weeks to months behind on the required updates.[9] Often, the most important machines are the least secured since technicians worried about patches breaking their logistics or scheduling database sometimes refuse needed security updates for months. Regardless of the criticality of the machines, infecting a few of them so that they begin "spewing traffic" (i.e., sending large amounts of data across the network) will quickly overwhelm the base network. Past base-network security exercises suggest that even the most poorly crafted phishing attacks find a few victims, while more sophisticated attacks can prove devastatingly effective.[10]

The necessary permissions (administrator accounts), training, and practical experience needed to respond to attacks now reside only within the units of the 67 NWW.[11] If, however, an attack has saturated a base network (i.e., the infected computers are sending so much data that no one can establish a connection with machines on the victim network), outside administrators will find themselves powerless to assist. Every network has bottlenecks and choke points: devices that can handle only so much data per second, authentication servers that can accommodate only a few thousand connections at a time, and security devices that block traffic when their queue of packets to inspect is too long. When these points reach saturation level, parts of the base network become cut off from each other and the outside world. The tools used by network technicians (at all levels) to maintain and repair their networks will then fail, unable to connect with distant computers (whether across a continent or across the street). Depending on the number of machines infected, the effects of the attack could range from a few buildings unable to connect to the network to most of the base populace unable to log in. In the more serious cases, technicians can resolve the problem only by physically removing infected machines for repair. Since modern network maintenance is predicated on fixing most issues remotely, physically finding and repairing infected machines can require days or even weeks—assuming that local technicians have the right tools to recover from the attack once they find the machines.

The aforementioned cyber attacks are relatively easy to perpetrate, conducted by a lone hacker or a small group working in concert. A country with a more robust cyber warfare program can unleash much more sophisticated attacks, potentially capable of controlling or even destroying significant numbers of machines on the network. A typical month uncovers more than a dozen security flaws in the software used by standard Department of Defense computers.[12] An attack based on one of these weaknesses before release of the patch could spread for hours or even days before technicians could stop it. Potentially, such an attack could cause a network outage lasting days or weeks, depending on the level of damage and the scope of the attack (local or worldwide).[13]

If these more sophisticated attacks, carried out on behalf of state actors, are likely in any cyber war—and future conflicts almost certainly will include both cyber and kinetic battles—then what preparations can we make?[14] We must take two important steps to mitigate the impact of such attacks on Air Force cyberspace. First, we need to discard the current AFNETOPS paradigm, which assumes that centralized experts will deal with attacks during wartime. These experts will be swamped and cut off from most of the bases needing their help. Technicians at the base level require training and experience to deal with major attacks when the base becomes isolated; moreover, they must have access to administrator accounts with enough privileges to act as "cyber first responders" to an attack without relying on the 67 NWW's experts for assistance. Second, the Air Force should learn how to operate during network degradation and outage.

There are ways to give base-level technicians the tools and training they need without disrupting the cyber chain of command. For example, encouraging base communications units to maintain small training or exercise networks offers a feasible way of improving base-level technicians' skills. The Air Force should ensure that each base maintains a few dozen network devices and computers with configurations approved by the 67 NWW; these systems could simulate and defend against threats—possibly with the assistance of intelligence or aggressor units. Serving as "cyber flight simulators" for network first responders, they would give base-level technicians critical practice in dealing with local threat scenarios and operating a network when higher-level support is cut off. In addition, even though giving these technicians too much control over their network may threaten unity of command, in emergencies they need access to administrator accounts that give them full control over their base network. This access should not be used—or even available—during routine operations, but it is essential that these accounts exist for use in responding to attacks. Finally, the Air Force should consider high-level training in network defense for significant numbers of key base-level technicians so they can deal with these attacks. Although doing so may prove expensive, the status quo is not sufficient to defend Air Force cyberspace. If the service is serious about AFNETOPS, it must provide base network defenders with the training and experience to use their tools effectively; otherwise, networks will remain vulnerable, regardless of who possesses administrator accounts. The Air Force must correct the serious vulnerabilities in the AFNETOPS structure, mentioned earlier, that threaten to cut off base networks from the network hierarchy. By letting some network functions devolve to base-level technicians in emergencies and by ensuring that those personnel have enough training to use these tools, we can greatly enhance the survivability of Air Force cyberspace.

Ultimately, such survivability is important because of the missions it enables across all domains. Whether network failure occurs via loss of an air operations center's situational awareness tools, collapse of just-in-time logistics, or delays in base alert systems, it leads to rapid decline in the effectiveness of most Air Force units.[15] Consequently, not only network technicians but also ordinary Airmen should adjust their habits to prepare for cyber warfare by adapting and learning to operate when their base network comes under attack. Even when local technicians can fix the worst of the damage, hours or (more likely) days will pass before the network resumes normal operating status. The Air Force trains its pilots to perform tactically without communications, yet few of its wings offer training on how to handle network isolation, degradation, or outage at the operational level. Individual wings (especially flying wings and equivalent units) must correct this omission by periodically assessing their ability to operate in the face of realistic cyber attack. This may entail simulating system outages, configuring a network so that a sham virus takes certain machines offline, mimicking a communications blackout for hours or days, or working with corrupted systems. Although putting an entire wing on an exercise network and having an aggressor unit launch actual cyber attacks may prove unrealistic, most base communications squadrons can simulate the effects created by those cyber attacks. By practicing the projection of airpower over multiple days while dealing with little or no network access, wings can prepare for future conflicts that will likely include disruptive cyber attacks.

Because major cyber attacks will soon become a common part of war, the Air Force must adjust accordingly to maintain national security in this new environment. By reducing overcentralization of the current AFNETOPS structure and by training all Airmen to perform their mission despite network damage, we can reduce the impact of cyber attack and ensure that network degradation does not produce catastrophic mission failures. In sum, both users and network technicians need to prepare for cyber war and understand the accompanying demands and limitations they will face. ✪

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Notes

1. See Qiao Liang and Wang Xiangsui, *Unrestricted Warfare* (Beijing: People's Liberation Army Literature and Arts Publishing House, February 1999). (Author's translation, with assistance from Man Tsang.) For an English translation of the full text, see "PLA Colonels: 'Unrestricted Warfare': Part I," in "Chinese Doctrine," Federation of American Scientists, http://www.fas.org/nuke/guide/china/doctrine/unresw1.htm. Written in response to Operation Desert Storm and the US shift to network-centric warfare, *Unrestricted Warfare*—a classic of modern Chinese military theory—discusses ways that China (and its peers) can negate US advantages in technology and tactics via various asymmetric strategies. Although not all of its predictions have come to pass, the work was in many ways visionary, representing one of the first Chinese texts to deal with cyber warfare.

2. Air Force doctrine defines *computer network defense* as "actions taken to protect, monitor, analyze, detect, and respond to unauthorized activity within the Department of Defense [DOD] information systems and computer networks." Air Force Doctrine Document (AFDD) 3-12, *Cyberspace Operations*, 15 July 2010, 52, http://www.e-publishing.af.mil/shared/media/epubs/AFDD3-12.pdf. Note that the cyberspace operations lexicon recently released by Gen James E. Cartwright, USMC, uses the term *cyber defense*; for most purposes, the terms are interchangeable. "Joint Terminology for Cyberspace Operations" (Washington, DC: Joint Staff, [November 2010]), 6, http://www.nsci-va.org/CyberReferenceLib/2010-11-Joint%20Terminology%20for%20Cyberspace%20Operations.pdf.

3. The term *base-level technicians* refers to maintainers of the local base network—typically members of the base communications squadron, often those in positions such as network operations/network control center, communications focal point, cyber surety, or cyber transport. This article uses *local* and *base* interchangeably to describe these Airmen, and *administrators* and *network technicians* to refer to the Airmen who run and maintain networks. For the sake of simplicity, this discussion omits the roles of units of the Defense Information Systems Agency, now part of US Cyber Command. Some of the actions attributed to the 67 NWW are actually performed by Cyber Command units (usually requested and coordinated by 67 NWW personnel). Typically, those units are as centralized as those of the 67 NWW, and the problems described in this article are the same, regardless of which unit's network operations and security center is in charge. Chapter 2 of AFDD 3-12, *Cyberspace Operations*, describes the basics of the relationship.

4. For historical reasons, each major command generally has an INOSC detachment handling the more routine aspects of core network services across the command.

5. Some experts speculate that recent attacks attributed to North Korea were tests of this type of attack. See Elinor Mills, "Report: Countries Prepping for Cyberwar," *CNET*, 16 November 2009, http://news.cnet.com/8301-27080_3-10399141-245.html. For a more skeptical analysis of that attack, see Kim Zetter, "Lazy Hacker and Little Worm Set Off Cyberwar Frenzy," *Wired*, 8 July 2009, http://www.wired.com/threatlevel/2009/07/mydoom/. According to P. W. Singer, the DOD leases 95 percent of its communication links from commercial providers, adding an extra layer of complexity to any response. See his book *Wired for War: The Robotics Revolution and Conflict in the 21st Century* (New York: Penguin Books, 2009), 200.

6. During the DDoS attacks against Estonia in 2007, which lasted for weeks, major banking and government systems were down for hours, and most Estonian networks were cut off from the rest of the world for several days. See Clark Boyd, "Cyber-War a Growing Threat Warn Experts," BBC, 17 June 2010, http://www.bbc.co.uk/news/10339543.

7. For a discussion of related issues, see Richard A. Clarke and Robert K. Knake, *Cyberwar: The Next Threat to National Security and What to Do about It* (New York: HarperCollins, 2010), 179–218.

8. "Phishing" refers to e-mails sent with malicious intent and modified to appear to come from a trusted person, firm, or unit. Whereas in the DOD's usage, phishing includes deceptive e-mails that install viruses, many other authorities limit the practice to deceptive messages that perform identity theft. For more information, see *Wikipedia: The Free Encyclopedia*, s.v. "phishing," http://en.wikipedia.org/wiki/Phishing.

9. For an overview of what less-experienced hackers are capable of with popular tools, see "Metasploit Express," noobz Network, 5 June 2010, http://www.n00bz.net/metasploit-express/. Note that experienced criminal hackers have capabilities far beyond these, and state-sponsored groups tend to surpass everyone else. At a recent conference, Lt Gen William T. Lord, the Air Force's chief information officer, observed that " 'we have over 19,000 (information technology) applications in the Air Force,' . . . noting that Electronic Systems Center's IT Center of Excellence at Maxwell Air Force Base-Gunter Annex, Ala., examined about 200 of them. 'All of them had over 50 vulnerabilities.' " Chuck Paone, "General Calls for Network Utility, Security Balance," AF.mil, 17 August 2010, http://www.af.mil/news/story.asp?id=123218114.

10. For a slightly less anecdotal example of the effectiveness of poorly crafted phishing, see John Timmer, "Users Are Still Idiots, Cough Up Personal Data Despite Warnings," *Ars Technica*, http://arstechnica.com/science/news/2010/08/users-are-still-idiots-cough-up-personal-data-despite-warnings.ars. This article uses the word *virus* in a general sense to describe all malware (malicious software); in fact, the attack described would use a combination of viruses and worms.

11. For more details, see "67th Network Warfare Wing," 24th Air Force, http://www.24af.af.mil/units.

12. In August 2010, Microsoft released fixes for 14 security flaws in the Windows operating system; this figure does not include security issues with other software such as Adobe Acrobat or Java. See "Microsoft Security Bulletin Summary for August 2010," Microsoft TechNet, 1 September 2010, http://www.microsoft.com/technet/security/bulletin/ms10-aug.mspx; and Emil Protalinski, "Patch Tuesday: Microsoft's Most Security Bulletins Ever!," *Ars Technica*, http://arstechnica.com/microsoft/news/2010/08/microsoft-patch-tuesday-for-august-2010-14-bulletins.ars.

13. Given the limited number of experienced network defense technicians, 67 NWW units might be forced to address issues one or two bases at a time within their area of responsibility, even after attacks have been brought under enough control that the bases are no longer isolated. If it takes multiple days to repair each base, then bases at the end of the list could face weeks of network degradation.

14. Even countries as "off-line" as North Korea have established cyber warfare programs. See Dan Raywood, "North Korean Cyber Warfare Unit Strengthened with Recruitment of 100 Hackers," *SC Magazine*, 6 May 2009, http://www.scmagazineuk.com/north-korean-cyber-warfare-unit-strengthened-with-recruitment-of-100-hackers/article/136235/; and Clarke and Knake, *Cyberwar*, 27. The deputy secretary of defense has stated that "more than 100 foreign intelligence agencies" target DOD networks. The tools and skills used in cyber espionage are largely identical to the ones needed for cyber attacks. See William J. Lynn III, "Defending a New Domain: The Pentagon's Cyberstrategy," *Foreign Affairs* 89, no. 5 (September/October 2010): 97–108; and Bruce Schneier, "Cyberwar," *Schneier on Security* (blog), 4 June 2007, http://www.schneier.com/blog/archives/2007/06/cyberwar.html.

15. For a discussion of vulnerabilities similar to those of situational awareness tools, see Clarke and Knake, *Cyberwar*, 170–73.

The Cyber Warfare Professional

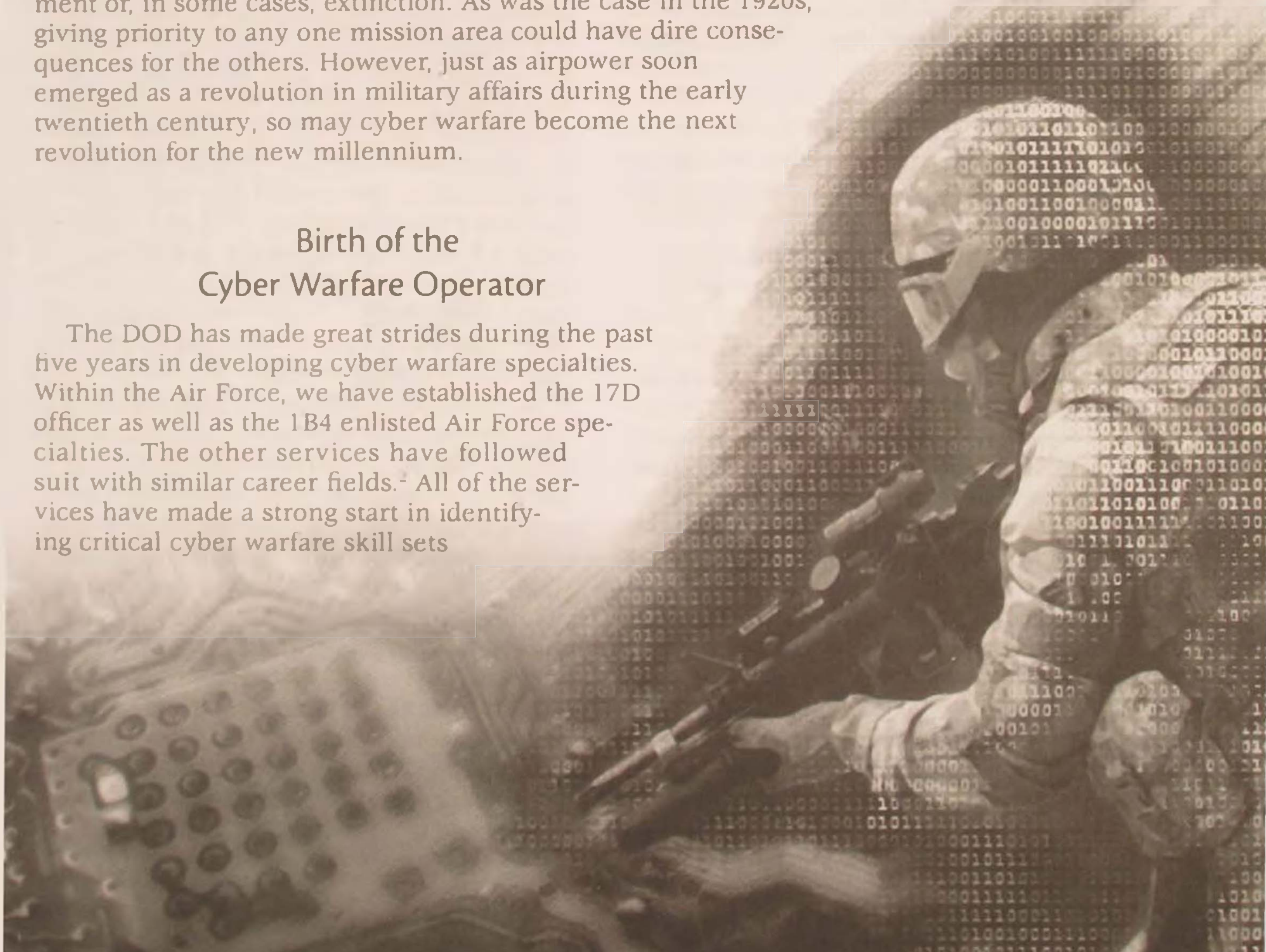
Realizations for Developing the Next Generation

Lt Col Timothy Franz, USAF

In 1924 US Army leaders faced the difficult decision of determining how they should distribute their budget within an increasingly fiscally constrained environment. Giving priority to any single mission area could mean disaster for the others. One particular program that attracted much interest—the Lassiter Plan, designed to expand the Air Service at an estimated cost of $90 million per year—would consume more than one-third of the Army's budget.[1] Today the US Air Force (as well as the Department of Defense [DOD], for that matter) faces a similar challenge. In the shadow of a poor economic climate, and in an effort to reconstitute our traditional capabilities, the DOD is undergoing sweeping cuts in both funding and manpower. Many programs face deep curtailment or, in some cases, extinction. As was the case in the 1920s, giving priority to any one mission area could have dire consequences for the others. However, just as airpower soon emerged as a revolution in military affairs during the early twentieth century, so may cyber warfare become the next revolution for the new millennium.

Birth of the Cyber Warfare Operator

The DOD has made great strides during the past five years in developing cyber warfare specialties. Within the Air Force, we have established the 17D officer as well as the 1B4 enlisted Air Force specialties. The other services have followed suit with similar career fields.[2] All of the services have made a strong start in identifying critical cyber warfare skill sets



and mature, formal, professional career paths. However, these specialties serve only as the first generation of what must inevitably become a much more diverse field of professionals.

This article explores four key realizations that we must consider as the DOD develops its next generation of cyber warfare professionals. First, since cyber war fighting is a team event, it requires constructive efforts from a broad range of professionals. Second, the diversity of cyberspace drives the need for a system that more effectively identifies and categorizes the technologies and functions within cyberspace. Third, we must expand the culture of today's cyber warfare professionals to one that encompasses war fighting. Finally, because cyber warfare capabilities can vary in sophistication, we require an effective means of illustrating those levels of sophistication. Although the content of this article and some of its examples draw on the Air Force experience, the concepts remain service-agnostic and appropriate to any organization developing cyber warfare capabilities.

Realization One: Cyber War Fighting Is a Team Event

We frequently hear people unfamiliar with the Air Force ask Airmen, "What do you fly?" However, just as successful air operations involve much more than skilled pilots, so do successful cyber warfare operations encompass more than just cyber warfare "operators." Rather, it takes a team of cyber war-fighting professionals, each with his or her own responsibilities and skill sets, to establish, control, and project combat power in and through cyberspace. Accordingly, we can group these professionals within four distinct roles. Cyber warfare operators plan, direct, and execute offensive and defensive activities in and through cyberspace. Cyberspace technicians provide and sustain assigned portions of cyberspace.[1] Cyber warfare analysts and targeteers offer intelligence support to cyber warfare operations. Finally, cyber warfare developers design and build cyber warfare tools and weapons.

Responsibilities and skill sets for each role differ, depending upon whether the position supports offensive or defensive operations. Offensively, cyber warfare operators employ cyber warfare weapon systems and tools from ground, air, or space platforms. To remain effective, they must maintain combat-mission-ready status qualifications in these weapon systems and tools as well as expertise in the technologies and functions of adversary networks and systems. Cyberspace technicians who support offensive operations maintain the cyber warfare weapon system and supporting infrastructure. Duties range from installation and configuration to troubleshooting and repairing the hardware and software components of their assigned platform. Analysts and targeteers fuse all-source intelligence to analyze adversary networks and prepare offensive targeting solutions for cyber warfare weapons and tools. Like cyber warfare operators, they must also be experts in the functional application of assigned network and system target sets. Finally, cyber warfare developers maintain engineering and software-development skills in order to ably construct new (or modify existing) weapon systems, weapons, and tools. Accordingly, the nature of developers' work requires maintaining expertise in the technologies of potential targets that their weapons and tools are designed to affect.

For defensive operations, responsibilities and skill sets of cyber warfare professionals differ somewhat. Cyber warfare operators assigned to these missions defend and control specified portions of cyberspace, which can range from a simple local area network (LAN) within a single facility or airborne platform to an entire global network. Regardless of the scope of responsibility, operators must be experts in the function of that protectorate and, to some extent, the technologies that comprise it. They employ defensive weapon systems and tools, and individual responsibilities vary, depending on the position assigned. Operators at the tactical level may control perimeter network sensors to defend against unauthorized attempts to access a network, while those at the operational level may direct large-scale, dynamic configuration changes in response to adversary attacks. Working hand in hand with cyber warfare operators in network defense, cyberspace technicians provide and sustain assigned portions of cyberspace. Like their operator brethren, their roles and responsibilities vary. Some technicians may be desktop computer experts, while others may have responsibility for infrastructure components such as routers and switches. Regardless, each technician must be skilled in the technologies and functions of his or her area of expertise and operate in accordance with mission priorities and defensive strategies established for the defended network. Intelligence analysts offer predictive threat analysis in support of defensive network operations. They fuse all-source analysis of technical, social, economic, and even political triggers in order to recommend proactive and, when necessary, reactive defensive measures to the cyber warfare operator. Such analysts must demonstrate expertise in adversary capabilities and tactics as well as maintain knowledge of the function and technologies of the networks they are charged to protect. Finally, developers for defensive operations have core skills similar to those of their offensive counterparts; however, they focus on developing cyber warfare weapon systems and tools that protect and defend networks.

Although every US military service has taken certain steps toward creating cyber warfare operators, they have made uneven efforts to professionalize the technician, analyst, and developer roles. Much as our predecessors deliberately sought to transform truck mechanics into aircraft maintainers and ground intelligence personnel into aerial targeteers, we must take further action to develop all cyber warfare professionals if we wish to produce a superior cyber warfare force.

Realization Two: The Diversity of Cyberspace

Cyberspace encompasses many technologies configured within networks that perform a broad array of functions. Although no universally accepted definition of cyberspace exists, most experts would agree that it is far reaching and includes a multitude of networked systems, ranging from the most common administrative networks (e.g., a home or office LAN), to space-based long-haul communications, to complex control systems for critical infrastructure assets. A closer look within any of these "functional" networks reveals different technologies (e.g., operating systems, communication protocols, software applications, etc.). Further, we find that technologies are not always exclusive to any one type of functional network. Rather, the same technologies may pervade different functional networks but with distinct applications for each. For example, the same network based on Microsoft Windows and Internet Protocol (IP) might be constructed in one manner to function as a banking service and in another to function as a manufacturing control system. In other words, the same technologies could have multiple functional applications.

To defend a network effectively, a cyber warfare team must understand both the technologies that comprise the network and the function it performs (i.e., the mission it supports). Although the makeup of an industrial control system versus an air and space operations center (AOC) network might demand similar technology expertise, the former has a completely different architecture, mission, and prioritization scheme than the latter (i.e., its function). In an offensive role, a cyber warfare team must understand the technologies of the target system as well as its function. On the one hand, comprehending the technologies allows one to select the correct weapon or tactic to gain access, escalate privileges, exfiltrate data, degrade enemy systems, and so forth.[4] On the other hand, understanding the function permits one to know how, when, and where to put "effects on target."

Today's cyber warfare professionals (both offensive and defensive) maintain expertise in only a very limited number of functional networks and technologies. Unfortunately, the threat is ubiquitous, requiring us to expand beyond our current scope of capabilities. Concerning our defensive capabilities, threats have graduated beyond attacks against common administrative networks and websites to demonstrate effects against critical infrastructure resources such as air traffic control and utility-managing supervisory control and data acquisition (SCADA) systems.[5] Offensively, key centers of gravity against which we would conduct operations include similarly diverse types of networks and technologies. Common military targets represent an assortment of functions constructed with a mix of commercially available and proprietary technologies that lie beyond our current offensive expertise. For both, we can reasonably assume that the sophistication level of the threat will only develop further with time. As the world slowly comes to the realization that cyberspace is the soft underbelly of many a nation (including our own), the United States will need to extend its war-fighting know-how beyond our present potential.

As the DOD expands its cyber warfare capabilities, we cannot simply say generically that we need more cyber warfare operators, technicians, or analysts, just as we cannot say generically that we need more pilots, weapon system officers, or aircraft maintainers. The Army Air Corps (and, later, the Air Force) found that no single pilot could expertly fly every airframe.[6] Similarly, no single cyber warfare professional can operate equally well across all of cyberspace. Every military pilot grasps the fundamentals of operating in the air, but each one specializes in specific weapon systems and missions. We will demand similarly discrete proficiencies of our cyber warfare professionals. Although all of them need grounding in the fundamentals of their domain, each must specialize in specific platforms, missions, and areas of cyberspace. Otherwise, the breadth of knowledge required for any individual to understand how to offensively affect or defensively protect all functions and technologies within cyberspace would take more than a lifetime of training.

Better management of cyber warfare capabilities in the future calls for a logical system that identifies and categorizes functions and technologies within cyberspace. One approach involves grouping technologies and functional networks by common characteristics or utility. For technology "classes," an easy-to-understand example would entail combining all UNIX variants into one class and all Windows-based operating systems into another. Some or all tactical digital information link protocols might form one class (e.g., Link 16, Link 22), while a collection of control system protocols (e.g., MODBUS, RP-570, or Conitel) might determine another.[7] Turning to the grouping of functional networks, we see that two functional "classes" might include banking networks and AOC networks. It may also make sense to organize some classes by geographic similarities or by the standards of a prevalent company. For instance, perhaps all water-utility control systems in the southeastern United States are similar enough to place them in the same class, or perhaps all chemical production facilities built by a specific company might share enough network similarities to fit logically into a single class. The preceding examples are not intended to resolve the divisions but only to illustrate the concept; actual classes could very well differ in size and composition. In any event, the formal establishment of logical classes of technologies and functional networks would assist in clearly identifying specialties and skill sets. Further, the modular nature of such a framework would offer many advantages in organizing, training, and resourcing cyber warfare capabilities.[8] The following points continue the illustration.

Applying Concepts: Offensive Example

Functional and technology "classes," if intelligently organized, would translate into skill sets that personnel could learn in a reasonable amount of time and that could be maintained within a structured continuous-training program.[9] Having individuals remain current in a certain number of functional and technology classes would allow easy assembly of the right team for specific missions. In the notional example that follows, an offensive cyber warfare mission calls for operational preparation of the battlespace against country Green's banking system. The known technologies for this system include IP-based and Windows 2000 technologies. Given this information, commanders select the following crew for the mission:

- Captain America (operator): An expert qualified in Technology Class B (IP-based, Windows-/UNIX-based technologies), he has a basic qualification in Functional Class R (banking systems) and is weapon-qualified in the "Babbage" weapon suite [fictional], which includes capabilities specifically designed to affect IP-based, Windows-/UNIX-based technologies.
- Senior Airman Good and Airman First Class Wrench (technicians): These personnel maintain the weapon system platform that Captain America operates and assist in the setup, loading, and configuration of the Babbage weapon suite.
- Lieutenant Wonder (cyber warfare analyst/targeteer): An expert qualified in Functional Class R (banking systems), she has a specialized focus on banks in Green's theater region and a basic qualification in Technology Class B (IP-based, Windows-/UNIX-based technologies).
- Mr. Hornet (weapon developer): A member of the team that designed the Babbage weapon suite, he is an expert in Technology Class B (IP-based, Windows-/UNIX-based technologies).

Extending our example, one can see how a modular class structure would have the added advantage of flexible crew pairings. Suppose a subsequent mission calls for disruption of country Orange's chemical production plant. Intelligence indicates that this system uses technologies similar to those of the banking system in country Green. In this case, the chemical production plant includes UNIX-based servers using IP-based protocols. The similarities in target technologies to those seen in the earlier mission allow the operator, technicians, and weapon developer to remain the same, while swapping out the cyber warfare analyst/targeteer in favor of more relevant functional network expertise:

- Captain America (operator): An expert qualified in Technology Class B (IP-based, Windows-/UNIX-based technologies), he has a basic qualification in Functional Class S (chemical production plants) and is weapon-qualified in the Babbage weapon suite.
- Senior Airman Good and Airman First Class Wrench (technicians): These personnel maintain the weapon system platform that Captain America operates and assist in the setup, loading, and configuration of the Babbage weapon suite.
- Staff Sergeant Braveheart (cyber warfare analyst/targeteer): An expert qualified in Functional Class S-4 (chemical production facilities built by Sunnybell Inc.), he has basic qualifications in Technology Class B (IP-based, Windows-/UNIX-based technologies).[10]
- Mr. Hornet (weapon developer): A member of the team that designed the Babbage weapon suite, he is an expert in Technology Class B (IP-based, Windows-/UNIX-based technologies).

As illustrated, the class concept allows us to more easily identify and select an appropriate crew complement to go against a specific target network. However, as cyber warfare matures, we can expect missions to target not only a single functional network but a combination of different interconnected functional networks. A broader example exposes how separate crews, identified by different functional classes, can integrate to produce more robust effects across a multifunctional network. For example, suppose a mission calls for disrupting power to one of country Orange's electrical power grids. Intelligence has shown that a certain SCADA system connected to a business LAN front end manages the target grid. Further, intelligence indicates that somewhere in country Orange a radio frequency link may serve as an access point into that business LAN.

The expertise required to exploit and gain access to the link, navigate around the defenses of the business LAN, and finally produce effects within the control system would be too much to expect of a single operator or crew. However, our class concept helps organize crews appropriately in order to complete the assigned mission. First, a crew qualified to exploit radio frequency communications (perhaps from a manned or remotely piloted aircraft) flies within range of country Orange to gain initial access. Second, another crew (qualified in the technologies and functions of the front-end business LAN) leverages the radio frequency access to enter the business LAN, overcome its defenses, and tunnel into the control system. This allows a third crew to remotely access the control system and disrupt power. Completing the operational picture, one can envision overhead assets (e.g., remotely piloted vehicle or satellite imagery) providing battle damage assessment in support of the ingress and egress of an air strike package or a special operations ground team. Although this example may seem too complicated to work, consider the complexity that goes into a single airborne strike mission. Similar to composite air operations, cyber warfare missions of this magnitude must eventually become commonplace.[11]

Applying Concepts: Defensive Example

When we discuss network defense in today's Air Force, we really mean only capabilities and forces that defend the Nonsecure and Secret Internet Protocol Router Networks (NIPRNET and SIPRNET, respectively).[12] However, if we peer within the fence line of most bases, we find many other networks critical to the successful execution of the Air Force mission. Examples include those that manage an installation's supporting infrastructure, such as utility control systems (e.g., water, electric power, and gas) as well as heating, ventilation, and air conditioning systems. Organizations such as security forces and the fire department rely upon networks that manage physical security sensors; fire alarm/fire suppression; and chemical, biological, radiological, nuclear, and explosive monitoring devices. Additional networks support airfield operations, radar systems, and airborne command and control (C2) links.[13] As we expand network defenses beyond the NIPRNET and SIPRNET, our concept of functional and technology classes proves useful by more easily identifying the systems we are charged to defend, as well as arranging the skill sets in which we must organize and train our cyber warfare professionals.

Like their offensive brethren, units assigned to the operation and defense of a network must maintain expertise in certain technology and functional classes. However, instead of focusing on the technologies and functions of target networks, these units must understand the functions and technologies of the networks they are responsible for defending. Applying our class concept to an example, we see that one unit may be designated to operate and defend Functional Class G networks (Patriot Battery Systems), and another designated to do the same for Functional Class J networks (electrical power SCADA systems). Accordingly, these units would include personnel who maintain qualifications in the designated functional class as well as in the relevant technology classes.[14]

Further Advantages to Categorizing Cyberspace

Beyond the benefits to the training and organization of cyber warfare forces, categorizing cyberspace within functional and technology classes offers other advantages through easier identification of war-fighting requirements. That is, suppose a combatant commander (CCDR) needs to degrade country Orange's integrated air defense system (IADS) X or defend US air control system Z. Requirements such as "degrade country Orange IADS X" or "defend US air control system Z" may be clear enough to determine needed conventional forces; however, such verbiage is difficult to translate into language useful for obtaining and apportioning cyber warfare capabilities. Breaking down requirements into functional and technology classes helps to more clearly articulate cyber warfare disconnects within the program objective memorandum (POM) process. In addition, it can assist the CCDR's planners in requesting appropriate cyber warfare forces from the services.

To illustrate the concept within the POM process, we could imagine translating the technologies comprising country Orange's "IADS X" into certain technology and functional classes. Inputs into the process would now effectively say, "We're requesting new (or more) manpower, weapon systems, training and education courses, as well as test and training ranges to affect these specific technologies and functional networks that comprise country Orange's IADS X." These disconnects, if fulfilled, will support the CCDR's requirement to affect IADS X. By articulating "POMable" cyber warfare requirements, we improve their chances of withstanding the scrutiny of funding panels. Furthermore, by tying them back to the needs of the CCDR, we also identify areas of risk if certain programs are not funded (e.g., if we do not fund the development of cyber warfare capabilities to affect IADS X, CCDRs must either assume risk in that area or fulfill the requirement through other capabilities). Obviously, this is a very simplistic example. Real-world instances would likely prove more complex since any single technology class might pervade many functional classes and, in turn, feed a multitude of the CCDR's requirements.

Having the ability to identify cyber warfare requirements more easily will also prove useful to the CCDR's planners when they assign capabilities within a "forces for" document, when they request service capabilities for contingency operations within an evaluation request message, or when they develop time-phased force and deployment data.[15] Today, such documents generically identify cyber warfare professionals. However, at some point, tasking a "cyber operator" will not be enough. For example, pulling someone knowledgeable about telephone systems will not help a CCDR who is looking for an expert in SCADA.

A logical system for categorizing groups of technologies and functions within cyberspace does not formally exist today.[16] However, we will need one if we wish to organize, train, and resource cyber warfare capabilities effectively in the future.

Realization Three: The Need for a War-Fighting Culture

The Air Force may have anointed our cyber warfare professionals with a new title and badge, but their culture must change if we are to morph them into the war fighters we envision for the future. Unfortunately, several obstacles slow our ability to establish a true war-fighting culture within this community. First, most of today's cyber warfare professionals come from the communications and information career fields. As such, they have historically focused on keeping communications up and running—not on completely understanding the missions supported by each communications link or node. Consequently, true understanding of mission impact caused by losing a link or node commonly occurs only after that loss takes place and customers begin to complain. A second cultural challenge comes in the way we currently define cyber war fighting. For example, at present we limit cyber "defense" primarily to detecting intrusions at the boundaries, discovering malware internally, and "blocking" what we find at the gateways, service delivery points, or firewalls.[17] Our cyber defenders need more familiarity with the full range of hostile threats to our information systems and more skill in fighting through attacks from such threats. The culture of today's cyber warfare professionals must evolve from one that provides service to one that offers a balance of service, security, and knowledge of threats, all in the name of mission assurance.

Developing a "war-fighting culture" for cyber warfare professionals means creating a different mind-set. On the offensive side, that mind-set comes more naturally because of the nature of the mission. However, on the defensive side, such a perspective takes extra effort. Networks support specific missions. One cannot adequately defend a network without knowing the mission that network supports as well as the threat that holds it at risk. Unfortunately, the "comm" culture historically has placed more emphasis on the health and availability of the network than on the mission for which it exists. We do need our cyber defenders to have expertise in the technologies of their networks; we also need them to have expertise in the supported missions, in ways of prioritizing those missions, and in knowing how degradation or loss of certain portions of the network affects those missions (before it happens). Further, our cyber defenders must know their enemy. Understanding the scope of the threat as well as its capabilities and limitations; common tactics, techniques, and procedures (TTP); historic and current trends; and primary motivations is critical to preparing for, prioritizing against, and maneuvering in response to that threat. Only by comprehensively understanding both the mission and the adversary can we even begin to effectively defend—and, ultimately, assure—missions in and through cyberspace.

Defensive cyber war-fighting actions consist of preparing for an attack, responding to it, and then recovering from it. Preparation entails establishing and securing the network. Fundamentals such as a defense-in-depth architecture, information assurance mechanisms, and strong C2 provide the foundation. Distributed sensors, both external and internal to the network, that detect, eradicate, and block threats round out the preparation. Responding to an attack translates to fighting through it. This means implementing such concepts as dynamic configuration controls (e.g., wartime IP addresses, frequency hopping, physically/virtually hot-swapping equipment), active deception techniques (e.g., honeynets), and the use of deliberately misleading server names.[18] In addition, our cyber warfare professionals must be able to quickly reroute blue (friendly) communications to secondary and tertiary paths when certain links and nodes are lost, as well as reroute red (enemy) attacks down innocuous paths. By understanding how the network supports the operational mission, defenders would know when and where we can afford to endure network disruption. At times, suffering a loss or degradation somewhere on the network would be acceptable if it doesn't affect a critical mission. If an adversary believes that his network attack is succeeding, he may continue to spend resources and time on an expendable target, permitting us to address other priorities. An effective defensive response also entails knowing how to fight integrally within the entire network C2 enterprise as well how to fight in isolation. It's one thing to defend a network with fully operational capabilities and C2 intact. It is quite another to do so after losing connectivity with the Integrated Network Operations Security Center, 624th Operations Center, or AOC. Can we still assure the mission? Response also includes striking back at the threat. Our defenders do not necessarily execute such actions directly (since offensive capabilities involve a completely different skill set); rather, those actions require coordinating through a C2 chain to allow an operations center or AOC to direct appropriate kinetic or nonkinetic responses. Finally, war fighting includes recovery activities such as reconstituting rapidly and in a prioritized fashion. Adequately trained cyber warfare specialists can do this effectively because they understand the mission, network, and priorities.

Realization Four: Not All Cyber Warfare Capabilities Are Equal

No cyber defense will repel every attack, and no cyber offensive capability will succeed against every adversary. A mechanism to identify the sophistication level of our cyber warfare capabilities is important if we wish to set clear standards for training and manage expectations of leadership. During events such as Red Flags or Air Force Weapon School exercises, air aggressors employ such a mechanism in the form of a "threat replication" matrix to identify the level of sophistication to which they will train blue forces in any particular engagement. For example, will they operate at a level-one threat intensity, representative of older enemy aircraft models and more basic TTPs, or will they fly at a level-four intensity, representative of the most advanced capabilities and TTPs employed by more sophisticated adversaries? Information aggressors are in the process of implementing a similar threat matrix to replicate an adversary's cyber warfare capabilities during training exercises. We will leverage this example to offer a concept for identifying the level of sophistication at which any cyber warfare capability is operating.

Table 1 represents a conceptual matrix for identifying the sophistication level of a defended friendly network. The first dimension of the level, labeled "technology," reflects the sophistication of the technologies used to operate and defend the network (for simplicity, the example matrix depicts only operating system technologies). A network operating at technology-level one might employ early operating systems such as an older Windows variant or a Sun system. At level two, it may use something more current or cutting edge such as Windows 7 or Snow Leopard. Level three represents an organically developed operating system or a trusted computing environment that may not be available commercially to the public (e.g., Next-Generation Secure Computing Base or Kylin).[19]

The second dimension of the example, labeled "TTP," represents the sophistication of the defensive TTPs employed. For example, level one might identify a network employing the most basic defensive configuration

Table 1. Sophistication levels for a defended network

		LEVEL OF SOPHISTICATION		
Defended Network		One	Two	Three
Administrative Networks	Technology	- Sun Operating System / Windows XP / Vista	- Windows 7 / Snow Leopard	- Next-Generation Secure Computing Base / Kylin
	TTP	- Simple LAN / Unpatched	- Defense in Depth / External/Internal Sensors	- Honeynets / Denial and Deception

typical of a simply configured, unpatched LAN. Level two might be organized with a more defense-in-depth approach along with external or internal monitoring mechanisms. Level three could reflect the most sophisticated network defenses we've seen, employing advanced techniques such as honeynets and deliberate denial-and-deception tactics. Bringing the two dimensions together, a network may operate with lower-end equipment (level-one technology) but have experienced operators who employ level-two TTPs. Or a network may have leading-edge equipment (level-three technology) but employ forces with relatively weak defensive training (level-one or -two TTPs).

Similarly, sophistication levels for offensive capabilities (table 2) identify technology levels by the complexity of the weapon system or tool employed. For example, level-one technology might consist of tools or weapons openly available on the Internet (e.g., "script-kiddy" tools), whereas level two could represent something more sophisticated, such as commercially available tools or weapons. Level three would reflect proprietary, organically developed offensive capabilities. TTP levels for offensive cyber warfare capabilities range from the least sophisticated, noisy, attributable ones (level one) to TTPs that employ advanced techniques (e.g., active deception, highly cloaked anonymous operations, etc.) capable of producing second- and third-order effects (level three).[20]

Identifying the sophistication levels of our cyber warfare forces has twofold importance. First, such levels translate to a better understanding of training standards. In other words, knowing these levels assists our cyber warfare professionals in identifying the level of sophistication at which they currently operate. Similarly, it helps them determine the level they need to attain in order to meet standards or to match or defeat known adversaries. Articulating standards not only defines training requirements but also builds operational rigor into war-fighting forces. Second, defining sophistication levels manages expectations of leadership. Manning, funding, and time are three investment variables which drive the sophistication level of any technology and TTP that we acquire or develop. Tools, like the matrix displayed, that illustrate the sophistication level of cyber warfare capabilities will help leaders more clearly understand what an investment will buy. Unless they maximize the investments, the resulting technologies and TTPs may be less than world class (i.e., level three) and therefore less capable than those of our adversaries. Understanding this point permits leaders to better understand and accept the risk, or reprioritize resources to attain the sophistication level desired.

Conclusion

In the last 100 years, airpower revolutionized military operations so completely

Table 2. Sophistication levels for an offensive cyber warfare capability

		LEVEL OF SOPHISTICATION		
Adversary Target		One	Two	Three
Administrative Networks	Technology	- In Wild Scripts / Tools	- More Complex / Commercial Off the Shelf	- Organic / Government Off the Shelf
	TTP	- Lone Points of Presence / Noisy / Attributable	- Multiple Points of Presence / Nonattributable	- N-Order Effects / Deception

that leaders around the world recognized air supremacy as essential to victory in war. In the next 100 years, the same may be said about cyber superiority. As the DOD further develops our cyber warfare capabilities, we need to address several realizations in order to bring us closer to success. These include establishing a strategy to cultivate all cyber warfare professionals (versus just the operator); creating a system that identifies and categorizes functions and technologies within cyberspace; developing a warfighting culture among our cyber warfare professionals; and utilizing an instrument that illustrates the sophistication level of cyber warfare capabilities. To address some of these realizations adequately, we will inevitably need to make significant investments. In today's climate of dwindling resources, how much will the DOD put into the future of cyber warfare? Our leaders face challenges analogous to those that confronted their predecessors in 1924. They made the correct choice. Will we? ✪

Notes

1. James P. Tate, *The Army and Its Air Corps: Army Policy toward Aviation, 1919–1941* (Maxwell AFB, AL: Air University Press, 1998), 28–34.

2. Henry S. Kenyon, "U.S. Army Ponders Cyber Operations," *Signal Online*, 15 October 2009, accessed 6 December 2010, http://www.afcea.org/signal/articles/templates/SIGNAL_Article_Template.asp?articleid=2082&zoneid; and "General Officer Programs," Navy Recruiting Command, accessed 6 December 2010, http://www.cnrc.navy.mil/noru/orojt3/generalofficer.htm.

3. Other terms are commonly used today to represent this role (e.g., "technician," "maintainer," "specialist," "communicator," etc.). The author chose the term "technician" because it appeared both adequate and less controversial than some of the others.

4. "Escalate privileges" is common cyber warfare vernacular for an attacker's efforts to upgrade his or her privileges within a network from normal user rights to those of an administrator in order to move freely within that network.

5. See Rose Tsang, *Cyberthreats, Vulnerabilities and Attacks on SCADA Networks*, working paper (Berkeley, CA: University of California, Goldman School of Public Policy, 2009), 5–6, accessed 20 December 2010, http://gspp.berkeley.edu/iths/Tsang_SCADA%20Attacks.pdf; *Global Energy Cyberattacks: "Night Dragon,"* McAfee White Paper (Santa Clara, CA: McAfee, 10 February 2011), 3, http://www.mcafee.com/us/resources/white-papers/wp-global-energy-cyberattacks-night-dragon.pdf; and *Review of Web Applications Security and Intrusion Detection in Air Traffic Control Systems*, Federal Aviation Administration, report no. FI-2009-049 (Washington, DC: US Department of Transportation, 4 May 2009), 4–5, http://www.oig.dot.gov/sites/dot/files/pdfdocs/ATC_Web_Report.pdf. SCADA systems are "used extensively by power, water, gas, and other utility companies to monitor and manage distribution facilities." See Harry Newton, *Newton's Telecom Dictionary*, 20th ed. (San Francisco: CMP Books, 2004), 725.

6. In 1925 Gen William "Billy" Mitchell identified three primary missions for an air force (pursuit, bombardment, and attack). See William Mitchell, *Winged Defense: The Development and Possibilities of Modern Air Power—Economic and Miliary* (New York: G.P. Putnam's Sons, 1925), 164–71. Today there are over a dozen missions, including counterair; strategic attack; airlift; air refueling; and intelligence, surveillance, and reconnaissance, just to name a few. See Air Force Doctrine Document (AFDD) 3-1, *Air Warfare*, 22 January 2000, 8–24, http://www.e-publishing.af.mil/shared/media/epubs/AFDD3-1.pdf. In 1921 fewer than 900 pilots were on active duty, with about two dozen different aircraft types in service. See Tate, *Army and Its Air Corps*, 19; and "Air Corps Development, 1919–1935," National Museum of the US Air Force, accessed 13 February 2011, http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=724. The US Air force now flies over 50 distinct aircraft types with more than 13,000 pilots, and each aircraft type has its own specialty code. See *Air Force Officer Classification Directory* (Randolph AFB, TX: Air Force Personnel Center, April 2010).

7. Protocols define the rules by which devices talk with each other; they comprise procedures or conventions relating to format and timing of data transmission between two devices and cover such

matters as framing, error handling, transparency, and line control. See Newton, *Newton's Telecom Dictionary*, 664.

8. Although this article addresses how the concept of functional and technological classes applies to military forces, it has application across the civilian and commercial sectors as well. A logical partitioning of cyberspace across functional and technological lines could help nonmilitary organizations organize their own networks more effectively.

9. There are more training variables to address with this statement, including how many functional and technological classes is reasonable for any individual to maintain, but the basic concept remains the important point.

10. For the purposes of this example, the hypothetical Sunnybell Corporation constructs chemical production facilities across the world. Its widespread presence makes it a good candidate for its own functional class.

11. The concept presented in this paragraph leads to the idea of identifying offensive cyber warfare units based on their ability to affect specific technology and/or functional classes. However, when one considers the multitude of differing technologies and functional networks in cyberspace, one realizes that it may not be practical to physically locate all expertise at one location (e.g., we'll likely never have enough personnel to give each offensive unit its own set of analytical expertise in railroads, electrical power, etc.). We must give additional thought to using a virtual network of functional expertise if we wish to implement these concepts successfully. For example, perhaps a pool of chemical production facility experts is physically distributed across the country, and these individuals can be linked together virtually. This would facilitate assignment of this expertise to different units at different times, depending upon the present mission. That is, Unit X is assigned to affect a chemical production facility on one day while Unit Y is assigned to affect a chemical production facility (perhaps the same one, perhaps a different one) on another day. However, perhaps both units share the same team of targeteers qualified in Functional Class S (chemical production facilities).

12. Network defense is the employment of network-based capabilities to defend friendly information resident in or transiting through networks against an adversary's efforts to destroy, disrupt, corrupt, or usurp it. See AFDD 3-13, *Information Operations*, 11 January 2005, 20, http://www.e-publishing.af.mil/shared/media/epubs/AFDD3-13.pdf.

13. Although some of these systems may occasionally ride the backbone of a NIPRNET or SIPRNET connection, network defenders are often unaware of their presence. In reality many of these systems are operated as independent networks and thus fall outside the operational area of today's network defenders.

14. This example uses a singular unit to illustrate the concept of applying functional and technological designations to cyber warfare units in an effort to spur further discussion. Actually the span and complexity of many networks may (and do) require the use of multiple units to cover all aspects of operation and defense. The topic of organizational structure for a complex network enterprise is hotly debated today within the cyberspace community and would require discussion outside the scope of this article. However, the general concept of applying functional and technological class designations to units and personnel charged with the operation and defense of networks is the salient point.

15. The secretary of defense's "Forces for Unified Command Memorandum" assigns forces and resources to combatant commands. See Joint Publication (JP) 5-0, *Joint Operation Planning*, 26 December 2006, I-26, http://www.dtic.mil/doctrine/new_pubs/jp5_0.pdf. CCDR planners use evaluation request messages to solicit course-of-action inputs from subordinate units. See ibid., I-15.

16. Although not formalized, a foundation does exist on which to build a logical categorization. The concept was first introduced in Maj Timothy P. Franz, "IO Foundations to Cyberspace Operations: Analysis, Implementation Concept, and Way-Ahead for Network Warfare Forces" (master's thesis, Air Force Institute of Technology, March 2007) as "network classes." It matured into a concept of "functional classes" and "technology classes" during the early stages of 17D/1B4 development by the Professional Cyberspace Education Working Group led by Headquarters US Air Force and then later within the Air Force's Cyberspace Technical Center of Excellence at the Air Force Institute of Technology. The effort has since ended due to manpower constraints, but the groundwork still exists.

17. The author acknowledges that more is involved than these actions, but they provide a good synopsis.

18. Physical hot-swapping is the process of replacing a failed component while the rest of the system continues to function normally. See Newton, *Newton's Telecom Dictionary*, 400. Whereas hot-swapping refers to swapping out a physical component, *virtually hot-swapping* refers here to the concept of swapping out a virtual machine or dynamically changing logical addressing in response to or in preparation for an attack. The au-

thor acknowledges that current technological advances do not fully support the concept of virtual hot-swapping today.

A honeynet is a network set up with intentional vulnerabilities to invite attack so that defenders can study an attacker's activities and methods and use that information to increase network security. See "Honeynet," *NetworkDictionary*, accessed 20 December 2010, http://www.networkdictionary.com/security/h.php. In the context of this paragraph, the term also indicates the use of honeynets to delay or deceive a potential attacker.

19. "Trusted computing" is defined as a locked-down computer architecture that can give guarantees about the application software it is running and that allows applications to communicate securely with other applications and with servers. See Mark Dermot Ryan, "Trusted Computing and NGSCB," University of Birmingham School of Computer Science, 2004, accessed 30 December 2010, http://www.cs.bham.ac.uk/~mdr/teaching/TrustedComputing.html.

The Next-Generation Secure Computing Base (NGSCB) is new security technology for the Microsoft Windows platform that employs a unique hardware and software design to enable new kinds of secure computing capabilities to provide enhanced data protection, privacy, and system integrity. See "Microsoft Next-Generation Secure Computing Base—Technical FAQ," Microsoft TechNet, accessed 30 December 2010, http://technet.microsoft.com/en-us/library/cc723472.aspx#EEAA.

Kylin is an operating system developed by academics at the National University of Defense Technology in the People's Republic of China and approved for use by the People's Liberation Army. Although the underlying infrastructure of this system is actually a UNIX variant of FreeBSD, for the purposes of this article, it offers an example of a close-to-proprietary operating system. See Rohit, "What Is Kylin Operating System?," *Spectrum*, accessed 13 February 2011, http://krititech.in/wordpress/?p=138; and Gerard, "Kylin, a Chinese FreeBSD Based, Secure O/S," *FreeBSD News*, 4 January 2011, accessed 13 February 2011, http://www.freebsdnews.net/2011/01/04/kylin-chinese-freebsd-based-secure-os/.

20. "Noisy" refers to a network attack vector that is highly detectable due to the unsophisticated tools and tactics employed by the attacker.

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Tools of Change

Tactical C4ISR and Conflicts—Past, Present, and Future

Thomas J. Rath

The United States does not have a single aircraft capable of performing tactical reconnaissance. Understanding this claim as it applies to irregular warfare (IW) requires defining the terms *tactical* and *reconnaissance*. In IW, *tactical* refers to the activities and actions of small units. It applies to tactical reconnaissance units themselves as well as the units they support and the enemy units they are trying to find. Tactical reconnaissance units can also support larger friendly forces and detect larger enemy forces, but their capabilities emphasize the small-unit level. In IW, *reconnaissance* means searching for enemy forces and their trails, campsites, supply routes, border access points, depots, and cross-border training camps. In essence, it means detecting the enemy's presence and gathering relevant data about terrain and weather. In IW, combining these two terms, *tactical reconnaissance*, secures a wide variety of information about the enemy, terrain, and weather for immediate use on the battlefield or for exploitation as an intelligence or surveillance task that would begin right away and generally remain with the tactical personnel covering the assigned area. The level of command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) integration between tactical units and those at the operational and theatre levels could expand rap-

idly, depending on the importance and exploitability of initial detection of the enemy. In Afghanistan, ground units detect the enemy first, most of the time. Airpower could contribute much more to the fight if the United States had a dedicated, manned tactical reconnaissance airplane.

The US Air Force is at least somewhat aware of its deficiency in tactical reconnaissance. A careful reading of *The 21st Century Air Force: Irregular Warfare Strategy* shows that the failure to provide a true tactical reconnaissance platform informs much of the document.[1] The "Purpose" section of this white paper speaks of the "Long War" and the need to initiate "new approaches and synchronize Air Force actions" by "fielding appropriate capabilities."[2] In "Strategic Context: The Challenges of 'Irregular Warfare,'" the document notes that the Air Force expects to be part of a "Joint Force" as well as "[work] by, with, and through partner nations . . . to establish a secure environment in which partner nations can flourish—ultimately without direct assistance"; however, it leaves open the means, particularly the aircraft, by which to realize this expectation.[3] The "Indirect Methods" portion of the section "Airpower in the Irregular Warfare Environment" virtually outlines the roles and missions of a manned, tactical-level C4ISR aircraft, and the "Direct Methods" portion of that section identifies mobility and intelligence, surveillance, and reconnaissance (ISR) as often "the most important elements" in counterinsurgency operations.[4] The section "Ends: Organize, Train, and Equip to Win the Long War" implies that we have not yet attained the essential capability to fight IW with our conventional warfare capabilities.[5] Next, "Ways: Five Pillars of Global Shaping" again outlines the need for a tactical-level C4ISR aircraft without specifically identifying it.[6] Further, "Means: Airpower for the 21st Century Irregular Environment" speaks of "'right-sizing' our enabling capabilities—such as ISR, cyber, and command and control—to meet joint requirements across the spectrum of conflict."[7] Finally, the sections "Risk: Failure to Anticipate, Adapt, and Learn" and "Conclusion" speak of adopting "new, relevant operational concepts," "learning from our own . . . experience," and applying "proven airpower principles in new and innovative ways to the environment we fight in today—and will continue to fight in tomorrow."[8] In this document, we probably have never had a more comprehensive outline of the need for an aircraft that the Air Force does not have. No other platform, current or proposed, comes close to addressing such a huge part of the Air Force's own strategy for the future as would a properly designed, dedicated, manned tactical C4ISR aircraft. The service should designate such a dedicated aircraft O/A (observation/attack) but have it function primarily as a C4ISR platform.

Far too many people in the Air Force and government believe in using slightly modified civilian aircraft and converted trainers to perform tactical reconnaissance. Traditionally the service has turned to such aircraft, but these planes are not adequate for this important and dangerous combat role. As discussed below, the history of aircraft used by the Air Force to perform tactical reconnaissance demonstrates a consistent shortfall in capabilities for dealing with the type of enemy forces typically encountered in IW.

A Brief History of Tactical Reconnaissance Aircraft

Today's deficit in tactical reconnaissance aircraft has deep historical roots. The first airplanes used in combat, the observation/spotter aircraft of World War I, accounted for the "O" designation that has stuck with that set of roles and missions ever since.

These planes soon became armed in order to survive, and any such aircraft today must have appropriate, effective armament. *Tactical reconnaissance*, from a German term, emerged in the 1930s to reflect the ability of aircraft to provide a light attack capability and much more information than simply observing and spotting for artillery. There followed an unfortunate split between what eventually became known as command, control, communications, and intelligence (C3I) roles/missions and observation/spotting, as if the two did not significantly overlap. The split, however, often resulted in using *tactical reconnaissance* to refer to any mission that sought out enemy troop movements. The term thus might apply to an O-1 flying at 1,500 feet and calling in an air strike or artillery barrage or to a TR-1 doing high-altitude photo reconnaissance for the regional combat commander. The first of those missions would be truly tactical, but the other would use a theatre-level asset for operational purposes. More recently, a set of tactical missions defined as find, fix, track, target, engage, and assess has emerged. Currently we assume that each of these tasks requires different aircraft. Finally, available technology has so expanded the range of possible roles and missions at all levels of war that a broader abbreviation—C4ISR—has emerged, which links the observation/spotting and C3I roles. Unfortunately, the Air Force has focused on integrating theatre-level assets into a complex C4ISR network, based on the incorrect assumption that they could also perform tactical-level C4ISR tasks. The very serious negative consequences of this misplaced emphasis inform much of this article.

Irregular wars are fought almost exclusively at the tactical level over an extended period of time, often upwards of 10 years. The United States has fought many such wars throughout its history. The military has learned how to fight those wars and has developed tools to do so, but the regular military services have quickly dismissed, discarded, and forgotten those things after each war. In particular, the Air Force has consistently resisted the development of aircraft dedicated to ground attack or true tactical-level reconnaissance. Its opposition to the development, procurement, and retention of the A-10 as a dedicated ground-attack aircraft is legendary.[9] Far less noticed has been the Air Force's reluctance to fund development of a true, dedicated, manned tactical reconnaissance aircraft. The institutional disregard for this capability goes all the way back to World War II.

During that war, Aeronca L-3s and Piper L-4s—unarmed, unarmored, and underpowered conversions of civilian aircraft—performed most American tactical reconnaissance. Enemy forces greatly feared these airplanes because of the destruction they could direct with high precision and effectiveness.[10] Notably, the crews received no stars on their shoulders during or after the war as a reward for their incredible bravery.

In contrast, the Germans designed and developed a dedicated tactical reconnaissance aircraft, the FW-189 Uhu.[11] A twin-engine aircraft with a pilot, navigator / radio operator, and observer/gunner, it offered an excellent field of view, a superb communications suite, more than twice the performance of the L-3 and L-4, ruggedness and maneuverability, and light offensive and defensive weapons. The FW-189 was a key element in German blitzkrieg tactics, proving very effective on the Eastern Front.

After World War II, the United States thoroughly evaluated Axis weapons, especially aircraft, except for the FW-189. Because it could not survive—much less perform tactical reconnaissance—anywhere near the American front lines, it received only a cursory review. In fact, *no* German aircraft—including the FW-190, widely considered one of the best propeller-driven fighters of the war—could survive 10 minutes over our front lines. The United States had suffered over 50,000 casualties to gain such total air dominance. Subsequently, the question of whether the Germans could have effectively used the FW-189 on the Western Front was irrelevant. The relevant question would have asked what American forces might have accomplished with an equivalent aircraft operating over and behind the German front lines under cover of such air dominance. We will never know definitively, but a couple of speculations might be useful. Would the Battle of the Bulge ever have occurred? Might American units have advanced well across the Rhine by late 1944, even under the diplomatic constraints that limited Gen Dwight Eisenhower's options? Still, the die was cast, and we have paid the price ever since.

In the first months of the Korean War, the shortage of tactical reconnaissance available to United Nations forces made the North Korean assault more rapid and effective than it might have been. After the Inchon landing, the Cessna L-19 saw extensive service but offered little significant improvement over the L-3 and L-4 of World War II, falling far short of the old FW-189. When the Chinese crossed the Yalu River, their troops and supplies traveled primarily on foot. The ill-equipped L-19 completely lacked the performance to track this massive movement. Eventually the Air Force had to employ old T-6 Texan training aircraft, which performed much better than the L-19 and proved more useful for tactical reconnaissance than any of the US or United Nations jet- or propeller-driven fighters. The Air Force's tendency to use modified trainers as combat aircraft thus began in Korea, and the United States has lacked a true tactical reconnaissance capability ever since. A Rand Corporation paper published in 1963 addressed the absence of effective tactical-level reconnaissance, or "A-frame detectors," beyond our front lines in that war, noting that the shortfall appeared to have become institutionalized, with dire prospects for the future.[12]

Despite the proven inadequacy of the L-19, now designated the O-1, it was still the only tactical reconnaissance aircraft initially available in Vietnam.[13] Its shortcomings led to employment of another slightly modified civilian aircraft, the Cessna 337, designated the O-2. Both of these aircraft had major deficiencies. Arguably a better observation/spotter aircraft, the O-1 was grossly underpowered and vulnerable, while the O-2 had a limited view from the cockpit, lacked armor, and carried little weaponry. The O-2 is important, however, because of what it might have led to and because of the Air Force's reaction to it. Cessna listened to critiques by O-1 and O-2 crews and designed the O-2TT to reflect their input.[14] The Air Force reacted so harshly that the O-2T test mule and the O-2TT mockup were dismantled and destroyed, their existence erased from Cessna's corporate memory.[15]

Meanwhile, the Air Force purchased and employed the OV-10 Bronco, which offered a significant improvement in performance, provided the crew a clear view forward and to the side, and carried a variety of weapons but failed to deliver as a consummate tactical reconnaissance aircraft. Designed to be all things to IW, it was master of none. The original design did not include a specific reconnaissance suite, and the rear seat had little instrumentation and none related to the reconnaissance role. Hence, the OV-10 simply became a light attack aircraft fitted with whatever equipment suite the Air Force decided to install. The service eventually fitted some of them with the Pave Nail suite while the Marines employed the Night Observation / Gunship System. Both suites failed to meet expectations because designers inadequately considered the aircraft's sound, visual, and other signature characteristics required for tactical reconnaissance in IW.[16]

Interestingly, the Army was studying one of those signature characteristics, sound reduction, through Lockheed's Q-Star and YO-3A aircraft.[17] According to reports, these highly modified, experimental powered gliders proved strikingly successful at night reconnaissance in Vietnam, but they had no other combat capability.[18] The Air Force did not participate in the YO-3A's development, evidently viewing it as competition for its own programs. Meanwhile, the service continued using modified trainers for combat duty by employing the T-28 in

Lockheed YO-3A. Reproduced by permission from Lockheed Martin Aeronautics Company

Laos and the A-37B (a highly modified T-37) in Vietnam. It later decommissioned the OV-10s, doubting they could continue to perform tactical reconnaissance duties without unacceptable losses. The Air Force then transferred the OV-10s and A-37Bs to various countries such as the Philippines and Thailand, which have used them extensively for counterinsurgency.

The Vietnam War supplied a treasure trove of tactical reconnaissance lessons; however, it is unlikely that any active duty Air Force officer can properly identify either the O-2TT or the YO-3A, or has read about the crews who flew light aircraft over Laos. Loss rates of different types of aircraft in the ground-attack role represent another Vietnam War lesson. An Air Force major wrote a study of aircraft loss rates that heavily favored using jet over propeller-driven aircraft in low-altitude ground attack. The significantly higher loss rates of propeller aircraft compared to those of jets, particularly in the case of the A-37B, are not reflected either in the Light Attack Armed Reconnaissance-Capabilities Request for Information (LAAR-CRFI) program's preference for a turboprop aircraft or in the sibling OA-X program.[19] Requirements that restrict candidates to versions of aircraft already in production limit both programs to current turboprop trainers.[20] The potential of a light, manned combat aircraft powered by small Pratt and Whitney or Williams turbofan engines for performing critical missions such as tactical C4ISR and light attack in both IW and conventional warfare remains unstudied. The Air Force should have learned the tactical reconnaissance lesson from Vietnam that converting civilian aircraft or trainers for combat duty seems acceptable in an office but seldom works well in combat.

Rather than study what might be required to fulfill tactical reconnaissance requirements, the service brought in a number of two-seat OA-10s for the first Gulf War, outfitting the observer with a pair of handheld binoculars, some night vision goggles, and a slightly better set of radios. Those planes also featured some changes in their weapons payload to reflect tactical reconnaissance demands. The Iraqis learned quickly not to shoot at a passing A-10 lest it attack, thus solving the issue of unacceptable loss. The Air Force does not appear to have seriously studied the positive and negative lessons available from the use of the two-seat A-10s. Instead, those planes proved to be an ad hoc solution.

When the Air Force participated in the initial invasion of Afghanistan in 2001, it brought no tactical reconnaissance capability to supplement theatre-level C4ISR assets. Fortunately, the allied Afghan forces had been battling the Taliban for years and easily made up for that shortfall. The price of having no real tactical-level reconnaissance capability came later during the battle for Tora Bora when the Taliban and al-Qaeda reportedly moved as many as 4,000 men plus 50 to 80 leaders unhindered through an unguarded pass to northeast Pakistan.[21] The failure to detect and stop these movements has greatly contributed to ongoing conflicts in Afghanistan and Pakistan.

The initial stage of the subsequent Iraq War was such an operational and strategic success that no one paid much attention to alarmed American unit commanders who reported that large numbers of Iraqi soldiers were leaving the battle areas still carrying their weapons. Nor did anyone pay attention to Saddam Hussein's claim that irregular units would carry on the fight long after the conventional war ended. The failure to understand and prepare for the possibilities of IW would cost us far more casualties than all the battles leading up to the collapse of Saddam's regime. Like their predecessors, the leaders of the Air Force—the service least prepared for this eventuality—turned to converted civilian aircraft such as the Hawker Beech King Air and the Cessna 208 to provide critical tactical reconnaissance in lieu of military aircraft specifically designed for IW missions.

Today, with the need for equipment more suitable to IW in Afghanistan having become undeniable, the Army and Marines are already receiving a second generation of weapons and vehicles designed to meet these requirements. The Air Force has done nothing other than install various ISR suites in various civilian aircraft, issue a CRFI for a LAAR aircraft, initiate an OA-X program, and use more remotely piloted aircraft (RPA). Once again, the leading LAAR/OA-X candidates are converted trainers, including the modified Brazilian Super Tucano A-29 under the Navy's "Imminent Fury" program and the AT-6B, a Swiss Pilatus PC-9 built under license by Hawker Beech as the T-6 "Texan II" and highly modified to compete with the Super Tucano. The Air Force was so uninterested in the inadequacies of the OV-10 that it did not keep even one plane it could modify to investigate ISR suites such as the one that has gone into the AT-6B prototype. Provision of even a baseline capability using the OV-10 would quickly have shown the total inappropriateness of the conventional configurations of the two trainers for armed reconnaissance. That inappropriateness has apparently become evident insofar as the original "OA" designation has been shortened to "A," and the "O" designation has been dropped altogether for both the A-29 and the AT-6B.[22] This highlights the primacy of attack in the eyes of the Air Force and its continuing disinterest in true tactical-level reconnaissance. However, noise and visibility signatures of conventional turboprop aircraft in IW and their radar signature in conventional warfare make their employment, even in light attack, extremely suboptimal.

Implications for Today

The Air Force has been so indifferent to tactical reconnaissance for so long that it can no longer even properly define the roles and missions.[23] The rapid development of technology has allowed tactical reconnaissance to take on the full range of C4ISR missions. Nevertheless, the modern Air Force, deeply committed to RPA development, has no real understanding of the necessity of a manned aircraft, no idea of the potential man/system synergies, no grasp of the required performance and critical aircraft signature parameters in IW, no analysis of a proper onboard weapons fit, and no study of how such an aircraft could fit into the overall C4ISR network. Nor does it have an awareness of the importance of a properly designed tactical C4ISR aircraft for the future effectiveness of its fifth- and upgraded fourth-generation aircraft at all levels of conflict intensity short of nuclear war. As an institution, the Air Force has shown little serious interest in the political and budgetary issues of long-term American involvement in foreign nations' unconventional wars, let alone the demands of a viable exit strategy in terms of equipping and training a developing nation's military—all of this despite some very good studies of many of these issues by Air Force personnel.[24] Ironically, the service has so distanced itself from the realities and demands of IW that it has no awareness—much less understanding—of the critical role that airpower must play in IW.

American and German experiences with tactical reconnaissance in World War II showed that it plays an important part in conventional warfare. But in IW, tactical reconnaissance—particularly the aerial variety—is the sine qua non of successful suppression and defeat of irregular forces. The key piece this capability rests upon a manned tactical reconnaissance aircraft that is dedicated, properly designed and equipped, and capable of carrying out the full C4ISR spectrum of tasks at the tactical level while providing full linkage to any available C4ISR net elements at the theatre level. This conceptual, advanced tactical C4ISR aircraft would be the modern American equivalent of the FW-189 mentioned earlier, although comparing the two would be like equating an F-22 and a P-51.

If irregular forces could effectively apply sufficient firepower against conventional forces of the sitting government, they would already be in power. The fact that they do not possess such firepower dictates the surreptitious movements of small units. These insurgent groups are difficult to detect when they disperse or move from one area to another. History shows that insurgent units are usually so small that they evade detection until they gather to attack. Despite all the advances in technology, finding these small units continues to rely on simple visual observation; everything else just supplements the latter, however useful the technology. In view of these realities, a true tactical-level C4ISR aircraft could offer initial detection, identification of a hostile force, eyes-on direction of a strike, confirmation of strike results, mobility, payload capacity and flexibility (both weapons and systems suites), options for viewing angle and viewing range, and a wide variety of communications capabilities.

Studies, articles, and exercises support these claims. A study that included Air National Guard responsibilities (the Air Force has traditionally given the Guard responsibility for "O" class aircraft) practically begged for a new forward air controller aircraft that offered more of these capabilities.[25] The October 1985 edition of *Air Force Magazine* included an interview with Lt Col Thomas A. Lanum, chief of the Ground Attack Division in Fighter Requirements at Headquarters Tactical Air Command, who said that "Tactical Air Forces have 235 forward air control aircraft. . . . We are working hard to get more and better ones."[26] A year later, the command decided that the program was too low a priority and cancelled it. Exercises at Fort Irwin, California, have consistently shown that an "O" class manned aircraft is absolutely necessary to carry out what used to be called "maneuver" warfare due to limitations that surface conditions impose upon ground reconnaissance units.[27] Because the constraints on surface tactical-reconnaissance units are the same in IW, the mandatory need for an aircraft designed to carry out tactical reconnaissance separately or in coordination with ground units, any available attack assets, or a C4ISR net thus remains unmet.

The Inadequacy of Modified Civilian Aircraft, Trainers, RPAs, and Theatre-Level ISR Aircraft for Tactical Reconnaissance

The implications discussed above highlight the need for a manned aircraft specifically designed for tactical reconnaissance. Slightly modified civilian aircraft or trainers are too detectable by enemy forces and vulnerable to enemy defenses.[28] Consequently, they must operate at such high altitudes that they offer little functional advantage over the theatre-level aircraft comprising the C4ISR net. However, modified civilian aircraft or trainers do have two distinct advantages: (1) their considerable cost savings over manned and remotely piloted military combat aircraft, and (2) the paucity of security and export barriers to transferring them to a developing country.

The latest favored trend, RPAs, is even less effective at C4ISR offensive operations against irregular forces.[29] Currently (and far into the future if we do not develop a manned tactical C4ISR aircraft) RPAs continue to rely on vulnerable, relatively immobile ground units for initial detection of irregular forces. Plagued by the "soda straw" phenomenon (the very narrow angle of view at mid-to-high powers of magnification), limitations in situational awareness, relative slowness to engage targets, and complete dependence on a very extended communications network, RPAs are far more expensive as a system than any comparable manned aircraft. Furthermore, they experience higher loss rates and require a phenomenal number of skilled personnel to carry out a single surveillance mission.[30] Basically, RPAs are remotely piloted strike platforms. In terms of the C4ISR mission, they excel only at surveillance, yet their employment in any C4ISR role may now have become counterproductive.

The Air Force's dependence on RPAs raises four main concerns. Ignoring them would amount to turning a blind eye to the shortcomings and vulnerabilities of a purely technological solution. First, Boeing has had a contract to provide RPA surveillance along the US-Mexico border for years but cannot make it operationally effective. This relatively simple program involves a static, linear, thoroughly mapped, uncontested area backed up by a stationary video surveillance system and a barrier fence system.[31] Due to ineffectiveness and high cost, program funds are now frozen, except for work along the Arizona border.[32] Second, the National Aeronautics and Space Administration has discovered a number of counterfeit computer chips in its satellites and space probes.[33] Since its systems checks are far more extensive and focused on far fewer pieces of equipment than the military's, one wonders how many weapons, communications suites, and other electronics-based systems such as RPAs contain counterfeit chips. Furthermore, might such chips compromise these devices? Third, hackers have deeply penetrated both the Pentagon and Congress, transferring a great deal of very sensitive information to mainland China, thus illustrating that our entire C4ISR net is vulnerable and subject to compromise.[34] The idea that new encryption will solve the myriad problems involved in such a deep penetration is illusory. Any aircraft or systems suite not capable of completely autonomous operations is unacceptably vulnerable.[35] Finally, any real-time RPA operation must use continuous communications and video feeds. We now know that the Taliban and al-Qaeda have been downloading RPA video feeds for some time.[36] Although their ability to download RPA video may be embarrassing, the greater problem is that irregular forces can now *detect* RPA feeds. It takes only a couple of relatively simple portable signal receivers to alert the enemy that an RPA is searching for them and to reveal both the aircraft's position and the nature of its scanning system. Small units don't need to download encrypted videos to know when to disappear by dispersing or hiding.

Despite the importance of these four concerns, another equally important fact pertains to RPA use in tactical C4ISR roles. After American forces leave, the allied government's military must continue to operate some sort of effective tactical C4ISR capability independently of US systems and support. There is little chance that the United States would ever give a developing nation a fully operational, highly advanced RPA squadron along with its codes and satellite access. There is even less chance that such a nation could operate it effectively at the tactical or even operational level, maintain the squadron over an extended period with any degree of effectiveness, afford it financially, or fully staff the unit with highly trained personnel. Furthermore, there is no chance at all that the access and control codes or operational manuals would remain secure for even a month.

By only lightly touching on the inadequacies of RPAs in tactical C4ISR, this article highlights the fact that the Air Force is so committed to RPAs for every role and mission that not even their demonstrated vulnerabilities can break the service's "target fixation." Thus, with every passing month the Air Force has less and less relevance to the real-time, real-life needs of developing nations now engaged in IW all over the world.

Aircraft used for theatre-level ISR are no better suited to tactical reconnaissance than modified civilian aircraft, trainers, or RPAs. A desire to make up for the shortfall in tactical reconnaissance motivated a request to upgrade the E-8Cs operating over Afghanistan so they could detect small units moving on the ground. This proposal has now grown to include Boeing's modernizing the Air Force's airborne ground-surveillance fleet with a P-8A-based design, or Northrop Grumman's significantly upgrading the E-8C fleet to enable these very large, scarce, and expensive aircraft to perform tactical-level reconnaissance searches for small, irregular units.[37] Unfortunately, these searches would be effective only when the irregular units move. The fact that a serious proposal exists for using a theatre-level 707- or 737-class aircraft for tactical reconnaissance reveals the complete indifference of Air Force culture to developing an effective manned tactical-reconnaissance aircraft. It also demonstrates how little the current Air Force leadership understands about tactical reconnaissance in IW. The service's entire approach is so far removed from the realities and demands of IW that it utterly negates the *21st Century Air Force: Irregular Warfare Strategy* mentioned previously.

In sum, not even the United States can afford to operate such a huge panoply of ISR assets that are only marginally effective, at best, in this kind of war. Nor can we afford to waste more time.

Characteristics of the Light Tactical C4ISR Aircraft That We Need

The C4ISR aircraft's three categories of detectable signatures are critical to its effectiveness. First, inherent signatures include sound generation, visibility (ease of seeing the aircraft), and infrared (IR) generation. The Air Force has paid no attention at all to sound generation, minimal attention to ease of visual acquisition (i.e., passive or active camouflage), and considerable attention to IR signatures. Second, externally generated signatures primarily involve the radar return from an aircraft to enemy receivers. In this area, the United States leads in stealth technology and jamming. Third, though not inherent to the operation of the aircraft, self-generated signatures entail the optional employment of its equipment such as onboard radar, communications gear, and lasers. The Air Force has worked very hard to reduce the signature of its aircraft radars but has been shocked at its communications suites' (including its video feeds') vulnerability to detection and has seldom even thought about the detectability of its lasers.

These signature categories affect the design characteristics of the aircraft and the effectiveness of its systems in both IW scenarios and conventional warfare. In the IW arena, radar signatures are unimportant. Irregular units cannot carry "mobile" radars with them and would not dare use them even if they had them because doing so would reveal their position. The Air Force needs to put personnel who write tactical C4ISR requirements not only into real tactical reconnaissance aircraft in actual combat but also with ground units so they can learn which aircraft signatures really matter to a terrorist or guerilla. Those personnel would immediately discover that sound is the primary signature recognized by people on the ground, whether encamped or moving across terrain. That signature becomes critical when a tactical reconnaissance aircraft is searching for encamped enemies who have hidden antiaircraft weapons (they therefore have a limited view and field of fire but can set up an ambush, based on the approaching sound). The Army has certainly become aware of this fact since its helicopters have come under increasingly effective fire.[38] However, we can passively ameliorate the sound generation of a purpose-designed tactical C4ISR aircraft to a very useful degree. Employment of active counternoise technologies could further reduce the sound signature to a level that would critically threaten irregular units. We need a platform that possesses such characteristics and permits such applications.

Susceptibility of an aircraft to visual detection from the ground represents the next most important signature in IW. We see images by contrast, movement, color variation, and shape. Movement and shape are inherent to an aircraft and afford minimal potential for reduction, but we can do a great deal to affect contrast and color variation. Several options are available, ranging from the simple and direct to the technologically advanced. The preferred option for now is a simple and inexpensive system involving underside illumination by directed, variable-color lighting from light-emitting diodes. A tactical C4ISR aircraft featuring reduced sound generation and low visibility poses serious threats to irregular forces that are tied to the inherent characteristics of those forces, making them very difficult to counteract.

The third most important signature, IR, mostly associated with engine exhausts, is not in itself a critical element in IW. Irregular forces have no IR search-and-track system to alert them to an otherwise undetected aircraft, but because we have made little effort to suppress the sound and visual signatures of our aircraft, their IR signatures have become a serious concern. Some irregular units already carry SA-14 and SA-18 man-portable air defense systems and may soon obtain an even later model, the SA-24. When sound alerts foot-mobile irregular units to an approaching aircraft, followed by visual acquisition, they generally have sufficient time to employ these IR missiles quite effectively.

In conventional conflicts, the reverse is true. The war zone contains a wide range of ground-based and airborne radars as well as numerous IR search-and-track systems, all directing a deadly variety of antiaircraft missiles and guns. Aircraft must have radically reduced radar and IR signatures if they wish to survive more than a couple of missions.

Interestingly, the seemingly disparate requirements for effectiveness and survivability in IW and conventional conflicts actually overlap significantly. Design characteristics that reduce sound and IR signatures in the IW arena can also diminish radar signatures. Additionally, the general configuration of stealth aircraft lends itself to enhancing a tactical C4ISR aircraft's crew performance. It also provides a clean underside that simplifies illumination efforts to reduce visual acquisition. Additionally, reduction of IR signatures is useful, regardless of conflict intensity.

The Air Force needs to take a serious, committed approach to the design requirements of tactical reconnaissance aircraft, hold the program to the most elegant approach (i.e., the simplest design that offers the largest margin of mission performance above the minimum requirements), avoid compromising the aircraft design by adding unrelated missions (armed tactical reconnaissance and the light attack capability inherent to any such design, as well as advanced training for such roles and missions, are quite enough), and, finally, prohibit the "gold plating" that major aircraft corporations agree to because they cannot afford to jeopardize their other bids and contracts with the government. (That type of acquiescence has distorted or killed many promising projects whose basic mission requirements now go unmet, or are met at too high a cost to acquire the numbers of aircraft needed.)[39]

Another important issue has contributed to the Air Force's reluctance to develop an aircraft capable of performing tactical reconnaissance: the apparent need for more than one type of platform to carry out the full range of such missions in low-, mid-, and high-intensity combat, particularly after the advent of powerful mobile radars. The author conducted a study in 1987–88 (as an outside contractor to the Air Force) that defined requirements for an "Advanced Manned Aerial Scout" based on input from aviators who had actually flown such missions in combat, as well as input from Army, Marine, and Air National Guard personnel involved in forward air controller exercises and tests.[40] Moreover, Eidetics International conducted an engineering feasibility study, demonstrating that a single aircraft meeting all requirements was well within then-current technology.[41]

Today's challenge regarding an evolved design lies in the cost of meeting the Air Force's stealth requirements while also designing for IW conflicts. As noted previously, a number of features meet the demands of both IW and conventional conflict. One requirement, the Air Force's demand for a very low radar signature, triggers a need for two variations of the same airframe. Cost and technology-security issues concerning the very sophisticated surface treatments that meet this specification make any export or transfer of such an aircraft very unlikely for all but our major allies. Still, production of an airframe in two versions, the sole difference being the surface treatment (the composition of the aircraft's exterior skin and canopy), may have a practical solution.

Domestic and foreign markets for such an aircraft are much larger than most studies have indicated since the latter are blinkered by policy constraints. The *VISTA 1999* study estimated a total global market of 800 airframes, but with the worldwide proliferation of IW, a much larger projected production run now seems reasonable.[42] The need for versions with and without such advanced surfaces might justify two production lines, one in the high-tech factory of a major defense contractor and the other operated by an innovative manufacturer of light aircraft. This solution also would allow for the different weapons and systems suites dictated by American and foreign demands. The potential markets should make such an aircraft program very cost-effective and fully justified even though it would add a new aircraft and engine(s) to the inventory. However, when one considers the number of modified trainers and civilian aircraft that these platforms would replace, the total inventory might actually see a reduction, as might the manpower requirements. The fact that the aircraft would be designed in America, built by American workers, and fitted with American weapons and systems suites might also represent a significant consideration.

Doctrinal and Personnel Implications of a C4ISR Plane

The Air Force would need to consider the doctrinal and personnel implications of any new aircraft it introduced. The use of modified civilian aircraft and converted trainers has imposed significant limits on C4ISR operational doctrine as it applies to manned aircraft. Because its capabilities affect virtually the entire current range of American military aircraft programs, a properly designed, highly capable, tactical C4ISR aircraft would necessitate rewriting the Air Force's IW doctrine. ISR shortfalls have forced the Air Force to use scarce E-8Cs for explicitly tactical-level reconnaissance, to have concerns about extending the service life of its F-15Es equipped with Sniper pods due to their heavy use in Iraq and Afghanistan, and to consider a whole range of transport aircraft modifications (including AC- and MC-130 variations, as well as, perhaps, C-27 variants) to provide fire support to ground units. After considering all of these issues, one begins to grasp the scope of doctrinal revisions that a true tactical C4ISR aircraft would allow and require.[43]

Operational doctrine for tactical reconnaissance itself must undergo a radical rewrite. Changing the current doctrinal floor of 1,500 feet (or 15,000 feet for the OA-X) for tactical operations to leaving the altitude flown and the decision to engage small units up to the crew members, based on their tactical judgment, reflects the extreme nature of the revision. However, every service's doctrines will need a significant rewrite as they apply to and are affected by a true tactical C4ISR capability. When one considers the level of authority that a single tactical C4ISR aircraft crew might have in implementing the intent of the operational commander in combat, the extent of change begins to boggle the mind. To paraphrase Napoleon, the aircrew truly would be carrying a "marshal's baton" in its kit.

Finally, with regard to career paths, pilots with "O" class flight time in their logbooks have traditionally had slim chances of promotion beyond the rank of colonel. The Air Force seems to think that such pilots must have regressed in some way since they fly the equivalent of basic or, at best, midlevel trainers. The service's promotion selection boards do not seem to value the fact that such missions are critical and that trainers and civilian aircraft are the only ones available to perform them.

The unique domain of tactical C4ISR aircraft has been called the "Indian territories," a historical allusion to the great expanses of the American "Old West" and, by inference, the scouts that made the US cavalry effective and ultimately victorious. In today's conventional warfare, the term refers to the ever-increasing space required between highly mobile and lethal major opposing forces prior to engagement. In IW it refers to all the territory not under direct control of friendly forces. In either case, the Indian territories are hardly empty or neutral; primarily they make up the domain of tactical reconnaissance on both sides. A properly designed, manned tactical C4ISR aircraft would be the top predator in these territories.

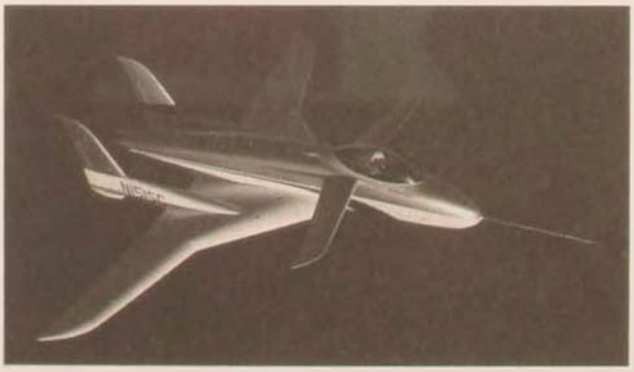
People who think of piloting an F-15, F-16, F-22, or F-35 as the ultimate in combat flying should consider the fact that in IW the crew of a tactical reconnaissance aircraft is likely to find itself more often engaged in different combat scenarios than any fighter or attack aircraft awaiting target assignments. If the United States ever again joins in a major conventional war, the tactical C4ISR aircraft will likely produce more aces than any fighter, other than the F-22, simply by virtue of opportunity. A properly designed tactical C4ISR aircraft is a true predator—a very high-performance aircraft within its domain and a very difficult opponent for fighters.

As an institution, the Air Force should also consider the fact that the crew of a true tactical C4ISR aircraft (the tactical reconnaissance platform properly fitted out with C4 equipment and an ISR suite) would often become the on-scene commander when involved in an engagement. The range of knowledge required, and the experience gained, might better prepare an officer to be chief of staff than would any other career in the military.

Conclusion

The twenty-first-century Air Force has options to quickly meet most of the Long War's demands with an effective and affordable light tactical C4ISR aircraft. It merely has to find a place in its culture to allow adoption of the innovative thinking that the service itself has sponsored. It could then follow up by rapidly implementing an innovative development and production program, perhaps by a small company consortium with combat experience in the IW arena and world-class design capabilities, rather than trying to persuade a big corporation to step out of its preferred pattern of corporate evaluation, bidding, and development. By doing so, the Air Force would avoid the normal minimum of three years to fly a prototype, an additional three years for initial deployment, at least a tripling of program costs, and delivery of a product too late to have any effect in Afghanistan.

We need a modern American analogue to the World War II–era FW-189. The Rutan 151 ARES—of the same weight, size, and thrust-to-weight class as the conceptual model of a modern tactical C4ISR aircraft—met all of the performance parameters required for the roles and missions over 20 years ago.[44] In particular, the ARES, powered by a JT-15D turbofan, meets the endurance and range standards on internal fuel alone. A dedicated tactical C4ISR design that meets all roles and missions demands as well as modern stealth requirements can be developed



Rutan 151 ARES. Reproduced by permission from Scaled Composites

relatively easily with demonstrated technical and engineering capabilities. We could quickly introduce an aircraft that would radically improve our ability to fight modern wars, particularly irregular ones. If the Air Force wants to implement its strategy for the twenty-first century, it has no other tactically effective or cost-effective option available today. We should have acquired such an aircraft 20 years ago, and we desperately need one now. ✪

Notes

1. *The 21st Century Air Force: Irregular Warfare Strategy*, Irregular Warfare White Paper (Washington, DC: Headquarters US Air Force, January 2009), https://www.nshq.nato.int/NSTEP/GetFile/?File_ID = 108&Rank = 0.

2. Ibid., 3.

3. Ibid., 4, 5.

4. Ibid., 5, 6.

5. Ibid., 6, 7.

6. Ibid., 7–9, especially the "Find, Fix, Finish, or Isolate Insurgents and Terrorists" portion.

7. Ibid., 9.

8. Ibid., 11.

9. Robert Coram, *Boyd: The Fighter Pilot Who Changed the Art of War* (Boston: Little, Brown, 2002), 232–37.

10. "Perhaps the greatest praise for their service came from a German prisoner of war: 'When the Cub flies over, all things cease. All we move are our eyeballs.'" Jan Bos, "The Flying Eyes of the Artillery," *WWII Quarterly: Journal of the Second World War* 2, no. 1 (Fall 2010): 97.

11. Leonard Bridgman, ed., *Jane's All the World's Aircraft, 1942* (New York: Macmillan, 1943), 79c–80c.

12. A-frames are the simplest type of shelter or storage structure, denoting the level of tactical reconnaissance required to detect not only the almost exclusively foot-mobile Chinese army of that time but also the type of reconnaissance necessary in virtually all variations of irregular warfare. Amrom H. Katz, *Some Ramblings and Musings on Tactical Reconnaissance* (Santa Monica, CA: Rand Corporation, 1963), http://www.rand.org/content/dam/rand/pubs/papers/2008/P2722.pdf.

13. Leonard Bridgman, ed., *Jane's All the World's Aircraft, 1956–57* (London: Jane's All the World's Aircraft Publishing Co., 1956), 248. Cessna developed the OE-2 for the Marine Corps. It had a more powerful engine and better performance as well as light armor, self-sealing fuel tanks, and specialized communications gear. Further, the OE-2 could carry either a 250-pound bomb or three rockets on each wing. The Air Force never purchased or used this aircraft.

14. John W. R. Taylor, ed., *Jane's All the World's Aircraft, 1969–70* (New York: McGraw-Hill Book Co., 1969), 304.

15. Cessna public relations executive, interview by the author, 1987. According to this executive, Cessna had never built such an aircraft. He could find no reference to it in the company's library or official history.

16. The number produced of either version never went beyond a test sample. The services retained neither the Pave Nail nor the Night Observation / Gunship System version nor made any attempt to upgrade the initial versions of these two suites for the OV-10.

17. John W. R. Taylor, ed., *Jane's All the World's Aircraft, 1971–72* (London: Sampson Low, 1971), 341–42.

18. See "Lockheed YO-3A Quiet Star," Western Museum of Flight, accessed 10 December 2010, http://www.wmof.com/yo-3a.htm; and *Wikipedia: The Free Encyclopedia*, s.v. "Lockheed YO-3," http://en.wikipedia.org/wiki/Lockheed_YO-3.

19. Maj Steven J. Tittel, "Cost, Capability, and the Hunt for a Lightweight Ground Attack Aircraft" (thesis, US Army Command and General Staff College, 2009), http://www.dtic.mil/cgi-bin/GetTRDoc?Location = U2&doc = GetTRDoc.pdf&AD = ADA510947. Major Tittel did not differentiate the A-37B from the other jet fighters, an unfortunate omission because the former flew missions far more similar to those flown by the A-1, OV-10, O-1, and O-2 than any other jet but had an astoundingly low loss rate. This fact should have generated much more interest. See also Fred George, "Low-Cost CAS COIN Candidate," *Aviation Week and Space Technology* 172, no. 28 (26 July 2010): 59–62.

20. "The USAF . . . wants its OA-X aircraft to cost no more than $10 million per airframe, to have an hourly operating cost of under $1,000, and to be built around a proven airframe, engine, and avionics with a demonstrable track record of service. The USAF is not specifying a powerplant for OA-X but circumstances seem to rule out anything except a small turboprop engine such as the 1,600 shp [shaft

horsepower] Pratt & Whitney PT6A-68 that powers both the Texan II and Super Tucano." Robert F. Dorr, "Special Report: Light Attack Comeback," *Combat Aircraft* 11, no. 4 (April 2010): 24–25.

21. Philip Smucker, "How bin Laden Got Away," *Christian Science Monitor* 94, no. 68 (4 March 2002): 1, 12, http://www.csmonitor.com/2002/0304/p01s03-wosc.html.

22. George, "CAS COIN Candidate," 57–62.

23. Two examples illustrate this indifference. According to Christopher Robbins, "Greg Wilson asked for a fighter assignment on his return. He was told over the phone by the officer in charge of military personnel control, 'We're trying to purge the Vietnam FAC [forward air controller] experience from the fighter corps because we have moved into an era of air combat where the low-threat, low-speed, close air support you did in Southeast Asia is no longer valid. And we don't want these habits or these memories in our fighter force.'" Christopher Robbins, *The Ravens* (New York: Crown Publishers, 1987), 339. As Marshall Harrison notes, "I was steadily learning my trade. I knew how many villagers should be in the rice fields surrounding each village. Too many might mean they had visitors. Too few could mean a VC [Vietcong] recruitment campaign was under way and the villagers decided to stay home until it was over. New footbridges had to be analyzed to determine what sort of traffic was using them, for the farmers seldom strayed away from their local village. A comparative surveillance of the bridges and trails would almost always show the amount of foot traffic in the area. It was impossible to hide movement in the wet season since tracks would show in the mud and elephant grass. I was starting to feel like something out of James Fenimore Cooper." Marshall Harrison, *A Lonely Kind of War* (Novato, CA: Presidio Press, 1989), 125. Compare this to what passes for tactical reconnaissance in the Afghan war, where an RPA flies at 15,000 feet or an E-8C flies at 25,000–30,000 feet.

24. See, for example, Maj William Brian Downs, "Unconventional Airpower," *Air and Space Power Journal* 19, no. 1 (Spring 2005): 20–25, http://www.airpower.au.af.mil/airchronicles/apj/apj05/spr05/spr05.pdf; Capt Vance C. Bateman, "Tactical Air Power in Low-Intensity Conflict," *Airpower Journal* 5, no. 1 (Spring 1991): 72–80, http://www.airpower.au.af.mil/airchronicles/apj/apj91/spr91/6spr91.htm; Col John D. Jogerst, "Preparing for Irregular Warfare: The Future Ain't What It Used to Be," *Air and Space Power Journal* 23, no. 4 (Winter 2009): 68–79, http://www.airpower.au.af.mil/airchronicles/apj/apj09/win09/win09.pdf; and Maj Richard D. Newton, "A US Air Force Role in Counterinsurgency Support," *Airpower Journal* 3, no. 3 (Fall 1989): 62–72, http://www.airpower.au.af.mil/airchronicles/apj/apj89/fal89/newton.html.

25. US National Guard Bureau, *VISTA 1999: A Long Look at the Future of the Army and Air National Guard* (Washington, DC: National Guard Bureau, 8 March 1982). (Pentagon Library, call no. UA42.A584). See the "Forward Air Controllers" section.

26. James P. Coyne, "Coordinating the Air-Ground Battle," *Air Force Magazine* 68, no. 10 (October 1985): 57, http://www.airforce-magazine.com/MagazineArchive/Documents/1985/October%201985/1085air-ground.pdf.

27. US National Guard Bureau, *VISTA 1999*; and US Army personnel, Fort Irwin, CA, interview by the author, 1987.

28. Captain Higgins, Headquarters Tactical Air Command, DFRG, interview by the author, October 1987. The command also dropped the program because of the vulnerability of any existing aircraft (e.g., conversion of a civilian airplane) trying to perform the forward air controller mission.

29. The latest RPA system, "Gorgon Stare," failed to meet numerous test criteria yet may still see deployment, a possibility that demonstrates the desperate shortfall in tactical level reconnaissance. See "Drone Spy System Fails Tests, Draft Report Says," *Los Angeles Times*, 25 January 2011, A9.

30. "Of the 195 Predators it has purchased, the Pentagon says 55 have been lost in Class A mishaps, meaning damage costing more than $1 million." Amy Butler, "Grim Reaper Rate," *Aviation Week and Space Technology* 170, no. 18 (4 May 2009): 24–26. See also Sandra Erwin, "Air Force Chief: We Will Double the Size of the UAV Fleet," *National Defense*, 6 October 2010, accessed 3 December 2010, http://www.nationaldefensemagazine.org/blog/Lists/Posts/Post.aspx?List=7c996cd7%2Dcbb4%2D4018%2Dbaf8%2D8825eada7aa2&ID=213. The article notes that the RPAs are "so labor intensive that each 'orbit' of aircraft requires 120 personnel per 24-hour shift."

31. "Even a relatively benign ISR curtain may not prove practical. 'Since the U. S. is unable to provide a "curtain" along our own southern border—even with fences to help—flying a few dozen or even a few hundred [RPAs] over foreign ground is unlikely to do better,' says David Rockwell, [an RPA] expert with the Teal Group, a Washington consultancy." John M. Doyle, "Boundary Issues," *Aviation Week and Space Technology* 169, no. 18 (10 November 2008): 57–58.

32. "Border Project," *Los Angeles Times*, 22 October 2010, A1, A20.

33. Jeff Bliss, "NASA Discovers More Counterfeit Spacecraft Parts (Update 2)," Bloomberg, 5 March

2009, http://www.bloomberg.com/apps/news?pid=newsarchive&sid=akUwVbu507m4.

34. Julian E. Barnes, "Pentagon Computer Networks Attacked," *Los Angeles Times*, 28 November 2008, A-1, A-30.

35. David A. Fulghum, "Digital Goes Viral," *Aviation Week and Space Technology* 171, no. 17 (9 November 2009): 74–76.

36. Siobhan Gorman, Yochi J. Dreazen, and August Cole, "Insurgents Hack U.S. Drones," *Wall Street Journal*, 17 December 2009, A1, A21.

37. Amy Butler, "Intelligence Choices," *Aviation Week and Space Technology* 172, no. 34 (13 September 2010): 44–48.

38. The same was true in Vietnam, as related by Major Harrison when he was shot down in an OV-10: "They'd probably been tracking my engine noise throughout the turn after I made the first pass, and they were lined up and ready. . . . I hadn't realized how loud the Bronco engines were." Harrison, *Lonely Kind of War*, 244.

39. For such projects, see, for example, Bettina H. Chavanne, "Humpty Dumpty," *Aviation Week and Space Technology* 170, no. 18 (4 May 2009): 28. The floundering Armed Reconnaissance Program is an attempt to replace the Army's gold-standard, gold-plated, and cancelled RAH-66 Comanche program with a helicopter that is not capable of meeting the ever-increasing requirements despite its skyrocketing costs. Robert Dorr writes, "It may prove difficult to develop a small, simple warplane that can fulfill a burgeoning roster of needs on the USAF's shopping list . . . some observers believe the list of requirements may defeat the purpose of seeking the lightweight qualities a Texan II or Tucano could offer, to say nothing of the flexibility and agility needed over the battlefield." Dorr, "Special Report," 24.

40. Thomas J. Rath, Robert Parker, and James R. Stevens, "A Study Identifying the Requirements for, and the Feasibility of, an Advanced Manned Aerial Scout," contract no. F33657-87-C-2161 (Wright-Patterson AFB, OH: Aeronautical Systems Division, USAF/AFSC, March 1988).

41. "A Study to Determine the Feasibility of an Advanced Manned Aerial Scout Airplane" (engineering study conducted by Eidetics International and attached to Rath, Parker, and Stevens, "Study Identifying").

42. US National Guard Bureau, *VISTA 1999*.

43. Marcus Weisgerber, "The Light Attack Aircraft," *Air Force Magazine* 93, no. 1 (January 2010): 56–58, http://www.airforce-magazine.com/MagazineArchive/Documents/2010/January%202010/0110aircraft.pdf.

44. Scaled Composites, http://www.scaled.com. Two releases detailing the history, design approach, dimensions, and weights as well as tested performance are available upon request.

Thomas J. Rath

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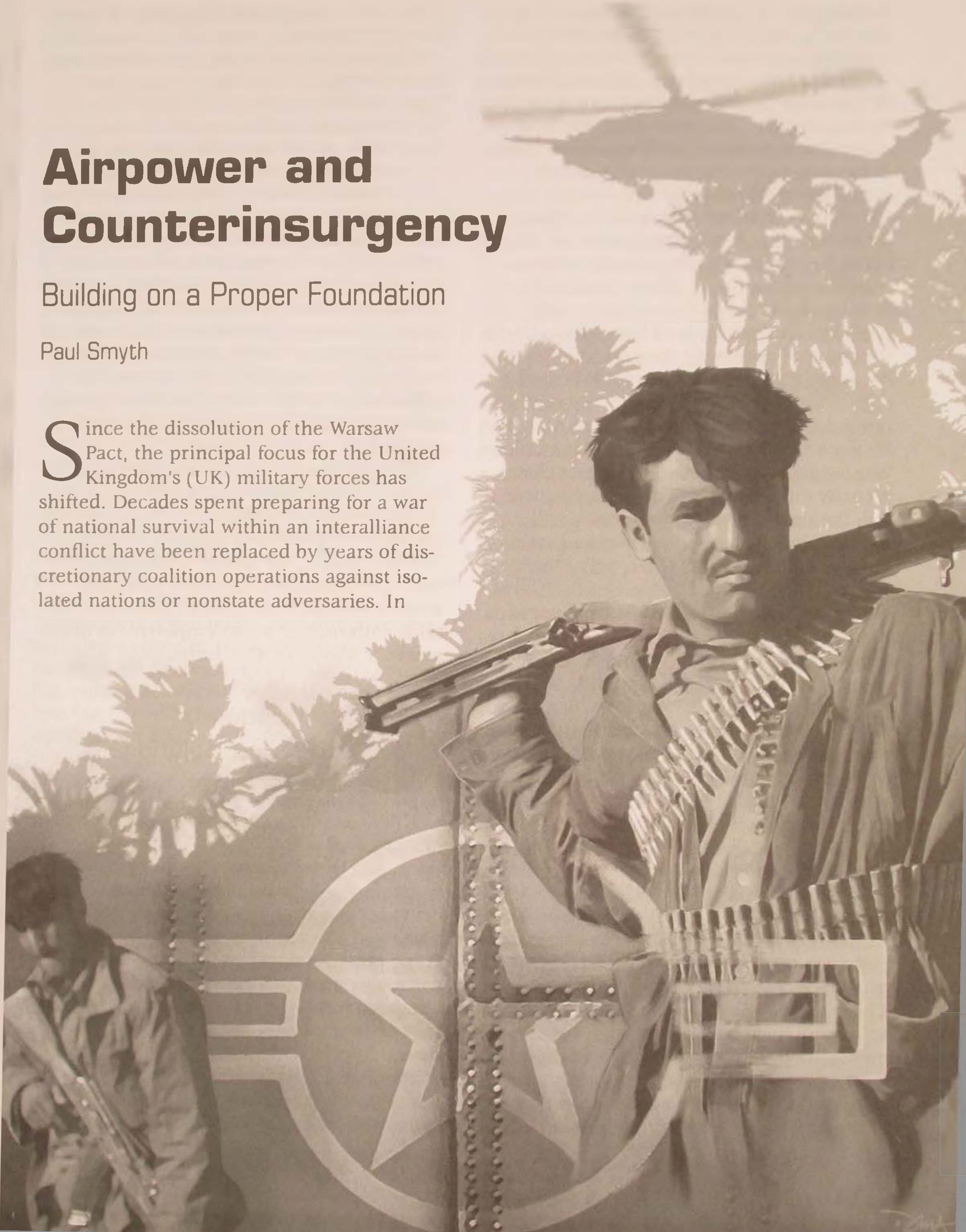
Airpower and Counterinsurgency

Building on a Proper Foundation

Paul Smyth



Since the dissolution of the Warsaw Pact, the principal focus for the United Kingdom's (UK) military forces has shifted. Decades spent preparing for a war of national survival within an interalliance conflict have been replaced by years of discretionary coalition operations against isolated nations or nonstate adversaries. In

Bosnia, Serbia, Kosovo, Sierra Leone, Iraq, and Afghanistan, Britain's armed forces did not battle against the enemy they had spent 40 years posturing to fight. Although many of the skills, tactics, and procedures honed in the Cold War had some utility in these subsequent conflicts, fundamental changes to the constraints placed on the use of armed force, the character of warfare, and the context to military operations demand more than the tweaked application of legacy capabilities. Rather, they dictate an elemental response in all three components of fighting power (moral, conceptual, and physical), and whilst land forces have borne the brunt of necessary changes, the Royal Air Force (RAF) must also evolve accordingly.[1] The need for such development is not limited to the RAF but is relevant to any air force that has to transition from a Cold War legacy to be effective in today's global security environment. The author hopes that the points made in this article will therefore resonate with a wider audience.

Airmen must match the timely, flexible, and effective practical responses they have demonstrated in distant theatres of operation with equally adept progress in the conceptual arena at home. The present counterinsurgency (COIN) conflict in Afghanistan has explicitly exposed how airpower's critical campaign contribution can promote either mission success or failure. Never before has airpower's participation in war had the potential for such contradictory effects. Consequently, when US Army general Stanley McChrystal served as commander of the International Security Assistance Force (ISAF), he placed serious constraints on the use of ISAF air assets. Airmen did not initiate this sea change in airpower employment, nor was it the result of Airmen reviewing airpower theory. Therefore, although Airmen may have reacted well to changing campaign requirements, room still exists for greater proactive engagement, and Airmen must energetically assimilate the doctrinal implications of the new global security environment, particularly the growing relevance of nonstate adversaries.

This article aims to promote the successful employment of air assets in unconventional conflicts, which, although traditionally viewed as "small wars" or a distraction from primary military tasks, have the potential to inflict defeat upon the most advanced armed forces in the world. It does so by considering the approach taken to optimise airpower's contribution to COIN operations. It is not concerned with specific tactics, techniques, and procedures but with the doctrinal context within which operational processes and tactical activities should be developed. It therefore focuses on the conceptual foundation for airpower's participation in COIN, not the building (tactics, techniques, and procedures) to be constructed on that foundation.

When addressing a new operational challenge or requirement that departs from accepted thinking, Airmen have three generic options: use a previous solution, create a novel answer to the problem, or modify an existing approach to meet the emerging need. This article considers these three options with respect to the employment of airpower in a joint COIN campaign.

Option 1: Use a Previous Solution—the Allure of Historic Success

Understandably, the instinctive approach has involved searching for historic solutions, and the challenges posed by conflicts in Iraq and Afghanistan have drawn observers to look at airpower's early years to see if perceived success in British imperial air policing provides dormant lessons that could solve current operational problems. This approach has some merit (since relevant lessons might exist), but it is routinely flawed by a lack of objectivity in historical analysis and a neglect of context. Notable pitfalls include an enthusiasm to equate disturbances in the British Empire with today's violence in Iraq and Afghanistan, a bias in judgment that places emphasis on seemingly common features (e.g., geographical locations, ethnic similarities, or the adversary's tactics) while neglecting factors that invalidate the comparison (such as social, moral, and technological issues). For example, the dread reaction of many "natives" in the British Empire to flying machines that were alien to them and the often imprecise application of violent force by those aircraft contrast starkly with today's technologically savvy "tribesmen" and the interpretation of impotence they draw from the precise, discriminate, and proportional way coalition forces now conduct air attacks.

Furthermore, when examining the British imperial experience, keep in mind that a significant factor promoting the deployment of RAF units to remote parts of the empire was pressure on defence expenditures. The political popularity of RAF air policing during the interwar period was perhaps due more to the economic benefits of using aircraft instead of more expensive land forces than to the limited operational capability of biplanes. Today, comparatively analyzing cost-effectiveness remains a complex issue encompassing factors such as the cost of platforms and the units that support them, the capabilities they provide, and their utility in COIN conflicts. In addition, the increasingly prohibitive costs of twenty-first-century aircraft programmes weaken the notion that employing airpower is a "cheaper" option, however capable it might be.

Objectively, the direct relevance of the imperial experience to current scenarios is questionable; overlooking this reality casts doubt upon the conclusions drawn from that chapter of airpower history. More seriously, to contrast the RAF's positive imperial experience with the difficulties that modern land forces have experienced recently in Iraq and Afghanistan is a deeply flawed comparison. Consequent efforts to promote an "air is best" agenda are incongruous when it is readily apparent that total air dominance and unprecedented levels of air and space capability (e.g., in intelligence, surveillance, target acquisition, and reconnaissance [ISTAR] assets) would not deliver inevitable victory in either theatre. Similarly, the argument that a "boots on the ground" policy brings an additional risk of casualties (which it can) and that we should reject it in favour of heavier reliance on airpower oversimplifies the link between presence and vulnerability (which can become inversely proportional); furthermore, it ignores the risk that a simple measure of casualties may distort the proper evaluation of operational effectiveness. Most importantly, recent experience in Iraq and Afghanistan clearly indicates that pursuing a COIN strategy which lacks the required physical ground presence to prevent nonstate actors from exercising authority over the population of a street, block, neighbourhood, village, or valley is inherently impotent.

Fighting a nonstate enemy who uses guerrilla tactics in populated environments demands a clear military imperative for more than an overwhelming air campaign. Israel's calamitous experience in Lebanon in 2006, the Iraq COIN campaign, and the conflict in Afghanistan have patently demonstrated that air supremacy and the freedom to use a panoply of modern air assets cannot secure terrain, stop enemy offensive activities, bring security to the population, prevent acts of personal coercion and intimidation, or arrest the spread of fear. Air supremacy can neither detect and deter corruption nor easily distinguish between friend and foe. Wars to win the support of a population demand engagement with the people—an engagement that airpower simply cannot provide. Air policing had demonstrable merit in the imperial period for suppressing recalcitrant natives, but against modern, fanatical nonstate actors who operate within the civilian population in an era of unrestrained media reporting, heightened legal scrutiny, and different economic circumstances, the imperial experience is of dubious value.

Despite an enthusiasm to scour historical records for examples of airpower's utility in difficult land campaigns, the notion that air assets can exclude the need for (or primacy of) land forces in a modern COIN campaign is erroneous thinking based on an overoptimistic interpretation of the value of historic experience, an inadequate understanding of COIN doctrine, and a neglect of the contextual landscape. Instead, to optimise their invaluable contribution to contemporary COIN operations, Airmen must do more than refer to previous success in an "age of empire."

Option 2: Create a Novel Answer to the Problem—Better to Start with a Blank Canvas?

In addressing how to use airpower in the present era of COIN campaigning, one would do well to consider if there is an advantage in starting with a blank conceptual canvas. Adopting such a method allows Airmen to approach the problem without preconceptions and apply their unique perspective on airpower with complete freedom. This technique is particularly effective when considering problems in which airpower comprises the principal military component, in which the challenge posed sits squarely in the air environment, or in which no preexisting solution to the problem is available. Unfortunately, this was not the case in Iraq, and, crucially, neither is it in Afghanistan. Once the short, conventional wars in Iraq and Afghanistan transmuted into insurgencies, the air component could not claim to be the dominant actor in either theatre, nor is the air environment the focal point of conflict, especially when one understands that the essence of a successful COIN campaign is to win the competition with insurgents for popular consent and moral legitimacy.

Paradoxically, the greatest obstacles to a distinctively air-orientated solution to fighting a COIN war are airpower's essential characteristics. Routinely listed as including speed, reach, ubiquity, and flexibility, they reflect use of the atmosphere as an operational domain and depend upon technology. Twenty-first-century airpower has come closer than ever to realising the aspirations of its historically overoptimistic proponents, but in expanding technological boundaries to new horizons, it has become less of a human endeavour in execution and increasingly constrained by the human element of the air dimension. This means that in COIN campaigns Airmen struggle with a fundamental difficulty since success in COIN demands engagement with the people who constitute the prize that friendly forces and the insurgents are contesting.

It remains an awkward truth that airpower, despite being wielded by humans, is principally machine power manifested through technology. Airpower has a huge contribution to make to COIN campaigning (e.g., in intelligence gathering or giving troops decisive manoeuvre capability), but it is irrefutably constrained by its own characteristics. Aircrews rarely see the recognisable faces of their adversaries, let alone the whites of their eyes, and few Airmen can give a reassuring shake of the hand to a frightened civilian. Ubiquity is a hollow omnipresence. Airpower enthusiasts may see the constant patrolling of an air platform over a village as "reassurance" in action, but it can do little to prevent verbal threats or indoor coercion. Fundamentally, to optimise their contribution to COIN activity, Airmen must recognise and accept the limitations of their capabilities and apply their invaluable services accordingly. This point should not be misunderstood. Humans are critical to the successful employment of airpower, but the idea that air operations are fundamentally a human activity is neither accurate nor helpful in defining airpower's role in COIN or irregular warfare against nonstate actors. For all its unique attributes and their undeniable benefits, airpower *cannot* claim that these qualities fulfil the COIN imperative for human interaction.

In COIN conflicts, technological supremacy is no guarantor of victory because success is anchored to political and societal matters such as ideology, legitimacy, individual will, personal interests, emotion, and perception—things that technology cannot determine. Thus, the omnipresent reconnaissance platforms commanding the sky above a conflict area employing sensors capable of gathering data day or night under most weather conditions cannot remove the essential requirement for human intelligence that comes from conversations, nods, inferences, eye contact, and other personal interaction. The complex intelligence requirements generated by a COIN campaign necessitate the inclusion of both technical and nontechnical intelligence sources. Air and space assets will therefore remain critical to building an effective intelligence picture, but Airmen must use the technological capabilities at their disposal with a realistic appreciation of their limitations in a COIN environment.

Although the key to optimising airpower's contribution to a COIN campaign lies in harnessing its unique capabilities to complement the capabilities of other actors, this does not exclude the need to maximize its inherent potential. For instance, the effect that airpower might have on perceptions (e.g., as a lever of influence or a method of shaping the battlespace) is an immature area of understanding that deserves concerted exploration. Since traditional tasks such as achieving control of the air domain may not burden the air component in a nonstate conflict, using airpower to optimum effect in a COIN campaign requires greater sophistication in its employment. This elegance must be founded on an understanding of what needs to be done and why, after which Airmen must then apply their professional expertise to derive how to use airpower to best effect.

In essence, the synergy that air and land assets clearly produce when used collaboratively should be replicated in the relationship between the theories underpinning the application of air and land power. A blank-canvas approach to developing a concept for the use of airpower in COIN or irregular conflicts does not facilitate this fusion of thinking. Rather, taking an approach related to existing COIN theory promotes intellectual synergy. Consequently, Airmen must become as familiar with relevant works by COIN theorists such as Sir Gerald Templer, Frank Kitson, and David Galula as they are with airpower exponents like Giulio Douhet, Air Marshal Hugh Trenchard, and Col John Warden. This is not a discretionary matter. If we are to integrate airpower into a COIN campaign to optimum effect, then this broadening of understanding is an essential requirement that we should immediately incorporate into the education of Airmen.

Airpower advocates must recognise that countering insurgency, terrorism, or banditry fundamentally requires engagement with people, and, therefore, in the security domain, it is preeminently a responsibility of land forces (both military and civil). Consequently, in addressing the problem of irregular conflicts against nonstate adversaries, one finds that an independently derived air-centric solution is of doubtful utility. Ironically, the very strengths that airpower brings to the defence and security realm place it in an ancillary position during COIN and irregular conflicts, significantly undermining the value of a blank-canvas approach to its employment. Furthermore, it would be illogical to pursue an independent air solution to combating nonstate actors when both the US and UK militaries have made huge efforts in recent years to improve the conceptual foundation for COIN operations. In the United States, this led to an Army/Marine Corps review of doctrine that culminated in the production of a new COIN manual.[2] In the United Kingdom, a corresponding reassessment has produced new joint and land doctrine for stabilisation and COIN operations.[3] Fuelled by continuing operations in Iraq and Afghanistan, the trans-

Atlantic review of previous thinking on COIN and irregular warfare has been intense, wide ranging, and progressive. To ignore the combination of vast practical expertise and intellectual rigour that military practitioners and academics have applied to the conceptual review of COIN would be virtual negligence. It is essential that Airmen start from the doctrinal height attained by those with prime responsibility for its conduct when they consider how to employ airpower in a COIN campaign.

Airpower's ability to bring overwhelming or decisive firepower to a COIN engagement accentuates the restraint that commanders must exert when employing it, especially when COIN priorities appear antithetical to traditional war-fighting considerations. Thus, "courageous restraint" has become a notable principle in Afghanistan, even when friendly forces are under insurgent attack. In a conventional interstate conflict, Airmen are encouraged to think and act primarily as Airmen; in a COIN conflict, their principal responsibility is to understand COIN. In the former, air component expertise has primacy over mission comprehension. In the latter, the priority is reversed.

The logical approach to attaining the desired level of airpower integration in a land-centric COIN campaign is to consider the problem from a common conceptual basis. Hence, the key to exploring how best to employ airpower in a COIN operation is not to embark on a blank-canvas exercise to derive an independent process or strategy, but to examine current joint- and land-force thinking about how to conduct such operations. If Airmen view this understanding through an "air lens," then they will intelligently consider the topic from an informed air perspective that encompasses not only a thorough awareness of what needs to be done, but also a full appreciation of airpower's capabilities, potential, and limitations.

Option 3:
Modify an Existing Approach—Build on a Proper Foundation

Extensive analysis by many military and academic authorities of historic counterinsurgencies has produced a number of principles of operation widely deemed enduring and consequently relevant today. Unlike the historical examination of imperial air policing, this scrutiny has focused on what needs to be done to succeed in COIN, not on the performance of a particular actor. As with fundamental theories such as the principles of war, subtle differences exist between and within nations on what these tenets are. Hence, the United Kingdom's Joint Doctrine Publication (JDP) 3-40, *Security and Stabilisation: The Military Contribution*, lists nine "Characteristics of Classical British COIN," while the new British Army Field Manual volume 1, part 10, *Countering Insurgency*, lists 10 principles for COIN.[4] Despite such variations, there is broad acceptance of principles such as the primacy of politics in a COIN campaign and the need for a political aim, the imperative for a coordinated pan-government approach, the importance of intelligence and information, the effective separation of insurgents from their base of support, the neutralization of the insurgent, the need for long-term postinsurgency considerations, and the need to protect the population.[5]

Regardless of the list we use, the principles are not prescriptive, and we should not apply them dogmatically. Nevertheless, they form a substantial part of the context for military activity and provide a useful conceptual framework that helps shape, inform, and constrain campaign planning. We should therefore apply them when employing airpower in COIN operations, especially since airpower's core attributes may give commanders military options denied to land forces, such as the ability to reach into remote areas or third-party states. The air component's capacity to conduct sorties independently of a land commander's scheme of manoeuvre and well beyond his or her area of operations places an additional responsibility on Airmen to conduct activities that contribute to joint mission success. This obligation includes ensuring that autonomous air action is both guided and constrained by relevant COIN principles.

Briefly, with respect to the listed COIN tenets, airpower's ISTAR and kinetic capabilities have obvious application in gathering intelligence or information and in neutralizing insurgents. However, Airmen should devote more thought and effort to exploring how airpower might have utility in supporting political, interagency, and postinsurgency endeavours. Whilst efforts investigating the innovative use of airpower (e.g., using an air presence to shape the ground environment) to broaden its contribution to COIN operations are welcome, it is important not to neglect how routine air activities (such as air transport) might be utilized to greater effect. Similarly, the positive effects of constraining the use of airpower merit greater attention, for it is clear that the overall COIN campaign in Afghanistan suffered when the legitimate use of close air support (CAS) caused civilian casualties and undermined popular support for ISAF, and that the heavily controlled use of airpower is a key aspect of ISAF's present campaign plan.

To optimise airpower's contribution to a COIN conflict, air commanders must not only follow the guidance found within the listed general COIN principles but also ensure that the tactical employment of air assets accords with the approach taken by the overall commander as described in his or her concept of operations (CONOPS). As with the COIN principles, national and other variations to a core approach exist. In US Army and Marine Corps doctrine, tactical activity is directed by the concept "clear-hold-build."[6] In JDP 3-40, it is encapsulated as "shape-secure-hold-develop."[7] In Afghanistan, ISAF employs a "shape-clear-hold-build" model.[8] Airpower should therefore be employed in line with both the overarching COIN conceptual framework and the applicable tactical methodology. This means that the air component's strategy-to-task planning process (which ensures that all sorties flown on the daily air tasking order contribute to strategic objectives) must reflect not only the contextual guidance and constraints found within the framework principles but also the tenets of the campaign commander's CONOPS.

If airpower is to fulfil its potential in a COIN campaign, then it *must* integrate its capabilities with the driving "clear-hold-build" scheme of manoeuvre. Though primarily a land-enacted CONOPS, this three-stage process is a joint and interagency responsibility, and air commanders should endeavour to guarantee that their employment of airpower facilitates its successful execution. While the listed COIN principles should shape the contextual requirement in which airpower operates, a number of factors should guide, inform, or limit how we apply airpower in a COIN campaign. The following factors should direct the air component's contribution to the campaign, and Airmen must articulate them to land commanders who may routinely view airpower as a subservient instrument.

First, *Airmen should employ airpower in accordance with the overarching joint campaign plan, not subordinate component or provincial plans*. Understandably, the land-centric nature of COIN operations has the potential to transform the land component's requirements into those of the joint campaign. But in a conflict demanding a joint and interagency response to produce a successful outcome, no single-component plan should usurp the primacy of the overarching campaign plan. In practical terms, this can result in air (and other) assets being allotted to the direct support of land forces when, in campaign terms, they might be more productively employed elsewhere. For example, aircraft used on preplanned CAS duties for potential troops-in-contact incidents cannot be patrolling remote borders used by insurgents to infiltrate from external safe havens.[9] This is not to downplay the critical value and battle-winning importance of CAS to troops but to recognize that with regard to *campaign* objectives, other priorities may equally rely on the employment of airpower and justifiably vie for greater attention. Where relative priorities lie and what emphasis they should receive are for the overall COIN commander to judge and direct, but Airmen must beware the potential lure of an overemphasis on single-component activities, guard against it, and when necessary be able to explain why other air tasks deserve higher priority within the joint campaign. Typically, this argument assumes greater weight when it is based on core COIN principles and the commander's CONOPS, so Airmen must assimilate them into their own thinking.

Second, *Airmen must ensure that their proposed contribution to a COIN campaign is within the art of the possible.* Whilst aiming to optimise their potential effect, they must understand those instances when they cannot accomplish their proposed mission and avoid giving overoptimistic assurances of what air activity can achieve. Similarly, they must prevent land commanders from forming overambitious expectations of what airpower can do for them. Responsibility for the realistic application of airpower rests squarely on air commanders, especially in scenarios in which force ratios, difficult terrain, or unit isolation creates additional difficulties for land forces and raises expectations of what airpower can deliver—expectations which are understandably reinforced by the freedom of air action that characteristically accompanies a COIN campaign against nonstate actors. In a scenario in which the enemy is barely able to interfere with friendly air operations, Airmen's plans and aspirations must remain firmly rooted in the art of the possible, and they must clearly explain airpower's true potential and limitations to other campaign participants.

Third, *Airmen must acknowledge that airpower can have a disproportionately adverse effect on a COIN campaign.* Despite the capacity of land-based weapons systems to inflict considerable collateral damage during COIN operations, civilian casualties from ground combat do not receive the same media interest as those resulting from air operations. In Afghanistan, of the thousands of sorties allocated to CAS, only a small fraction have caused civilian casualties, yet it is these aberrations that have often defined the public, media, and political perception of what airpower is doing there.[10] The harm caused by collateral incidents should not be ignored. Such events have seen the Afghan government call for a review of the legal framework for ISAF forces and the Afghan Senate cease business for a day in protest, whilst in September 2009 the death of many (perhaps over 100) civilians due to air attack in the German sector of Afghanistan led to the resignation of very senior military and political officials in Germany.[11] The need to constrain airpower is self-evident because an Afghan demand that kinetic air operations cease would create serious friction between the sovereign regime in Kabul and the international coalition supporting it.

Fourth, *Airmen must recognise that the traditional primacy afforded kinetic air roles may be reversed in a COIN campaign, in which "doing" less may achieve more.* Understanding the enduring principles of COIN campaigning would help Airmen recognise when a clear difference exists between what airpower could do and what it should do. In Afghanistan, CAS has proven tactically crucial and decisive, undoubtedly rescuing or protecting hundreds of ISAF troops unfavourably engaged with insurgents. Yet as noted previously, CAS can produce significant problems. The notion that kinetic activity should be airpower's principal contribution to a COIN campaign rests on a combination of skewed historical analysis and a legacy of Cold War demands and practice. Such thinking is unhelpful when the use of lethal force may actually swell—not diminish—insurgent ranks. Whilst bombing and strafing may have crucial utility at a given time and place, it is imperative that Airmen assign as much priority to other tasks which may have greater beneficial impact on the progression of the COIN campaign. For example, activities such as delivering agricultural assistance to isolated villages, transporting a clan chief's sick child to an emergency medical facility, or monitoring the internal communication lines of an insurgent group may appear less important than CAS yet yield more enduring effects on the campaign.

Fifth, *in their promotion of an air component's contribution to COIN campaigns, Airmen should emphasise the features of airpower not routinely recognised by other campaign participants.* In doing so, Airmen's reverting to the COIN principles outlined above would usefully guide their thinking and add substance to suggestions about how air assets might provide the greatest value to the COIN campaign. Whilst airpower's kinetic dimension has some obvious applications (e.g., helping clear insurgents from an area) and its ISTAR capabilities have utility across the whole COIN CONOPS, its wider utility—particularly in the "build" stage of the process—is less obvious and deserves specific attention. Executing a clear-hold-build or shape-secure-hold-develop strategy is a complex and demanding task made exceedingly difficult without recourse to airpower. When a COIN commander seeks to clear an area of insurgents, the surveillance, kinetic, and manoeuvre options that air assets provide to land forces may prove critical to success. This is especially true when those land forces are employed in less than overwhelming numbers, deployed to inaccessible locations, or fighting in areas clear of civilians. Airpower's contribution may be equally important to the sustainment of such forces during a holding phase, while air-based firepower remains a responsive means of interdicting the reemergence of insurgent forces. Air transport assets might also contribute to the building phase of a COIN campaign, but this potential should not be overplayed because, by that stage of the campaign, the prevailing security situation may allow safe movement by land. Lastly, Airmen should remember that throughout the entire clear-hold-build process, air and space assets can provide the psychological benefits of an air presence; round-the-clock ISTAR coverage; and command, control, and communication capabilities that a reliance on digitalisation has made indispensable to military operations.

In their promotion of an air component's contribution to COIN campaigns, Airmen should emphasise the features of airpower not routinely recognised by other campaign participants.

Sixth, *Airmen should not underestimate the value of their contribution to the development of indigenous forces.* An essential feature of progress in a COIN conflict is the emergence of capable indigenous security forces. Whilst infantrymen or policemen can be trained relatively quickly, enabling capabilities such as airpower that allow them to operate independently and sustain their activities take much longer to develop. This imbalance can minimise the potential impact of improving native security forces, for example, by limiting their ability to deploy and establish a credible presence amongst their own population. Therefore, the allocation of foreign aviation assets to tasks that serve indigenous forces could possibly have a disproportionate effect on promoting local perceptions of those forces. A significant benefit might also accrue from providing support to indigenous officials (e.g., provincial governors) who would otherwise struggle to reach much of the area under their jurisdiction. Undoubtedly, the substantial effort invested in partnering and mentoring indigenous security forces should include air assets and capabilities, and because training the technically skilled personnel needed in a new air force will take considerably longer than the time required to produce infantry and policemen, this investment should start at the earliest opportunity. For instance, whilst the extensive efforts of the Combined Air Power Transition Force in Afghanistan are contributing to the development of a fully capable Afghan air force in a wider COIN setting, they reinforce the importance of an early allocation of sufficient resources to the task.[12] One hindrance to development here is that to make an effective COIN contribution, indigenous air forces do not need to operate the sophisticated equipment used by foreign partners, yet modern air forces do not operate the cheaper, less-capable aircraft that would suit their emerging counterparts. Although this does not prevent mentoring, it would obviously be easier to convert indigenous air and ground crews to types of aircraft flown and serviced by the partnering militaries. In Afghanistan the absence of a basic ISAF-operated air platform capable of reconnaissance and ground attack—that meets the demands of a COIN campaign against nonstate actors—impedes the timely development of Afghan airpower. US plans to procure a light attack/armed reconnaissance (LAAR) aircraft with sufficient utility for COIN-type conflicts offer a sensible progression that may facilitate the future development of indigenous forces and see COIN theory shape procurement policy.

Conclusion

Airpower's core attributes (i.e., its speed, reach, ubiquity, and flexibility) remain invaluable in COIN operations, but, critically, they also limit its contribution. Although the United States and United Kingdom have made excellent progress in the practical application of air support to ground forces, additional conceptual effort is necessary to optimise the contribution airpower could make to COIN and irregular conflicts. This deficiency undermines the outstanding efforts that characterise airpower's daily contribution to ongoing conflicts. In light of an aggregate of over 13 years of combat experience across two theatres, the scarcity of specific air doctrine on the employment of airpower in a COIN campaign is startling. One may argue that the main body of land and joint doctrine manuals contains implicit references to airpower, but explicit references occur less frequently: the British Army's COIN field manual includes a five-page section on airpower, the 200-page US Army Field Manual 3-24/Marine Corps Warfighting Publication 3-33.5 on COIN also has just a five-page annex on airpower, and the similarly large UK JDP 3-40 refers to airpower only once.[13] Neither does there appear a surfeit of air-authored COIN doctrine on either side of the Atlantic. This paucity of relevant air doctrine should be addressed, and the responsibility for that effort solely rests with Airmen, both in the development of air doctrine and their contribution to joint publications. However, attempts to produce such doctrine through an inappropriate review of history reflect misguided enthusiasm, while pursuit of an independent solution without explicit reference to concepts that underpin COIN operations in the land domain is both illogical and short-sighted folly. Perhaps the most pressing need is to apply airpower in accordance with the clear-hold-build concept of operations; importantly, however, the most informed suggestions for doing so must come from Airmen.

Through various means, the essential change that Gen David Petraeus enacted in Iraq (with remarkable results) involved switching COIN focus from the insurgents to the Iraqi population.[14] This led to the adoption of many different, often novel, approaches by land commanders and their troops. A similar review of how to employ airpower is overdue, especially when collateral casualties dramatically confront the notion of protecting the civilian population. Dealing with nonstate actors in scenarios that do not fit within a conventional conflict framework poses new problems for Airmen. All military operations, including air activities, must reinforce and not undermine the moral authority of friendly forces. With the rising importance of nonstate actors, the boundaries between conventional war, insurgency, terrorism, and criminality have blurred, and these differing security threats regularly overlap or coexist. Today, Airmen must contend with complex scenarios in which insurgency, internecine conflict, terrorism, and violent criminality occur simultaneously across the same battlespace. For example, is the group that an air asset detects illegally crossing a border a terrorist cell transporting weapons and explosives or petty criminals smuggling contraband? Are the men loitering around an electricity pylon planting a bomb or stealing copper? The additional challenges that this complexity generates for friendly security forces affect not only Soldiers and policemen but also Airmen since the answers to such questions routinely dictate a different military response.

For all their progress in addressing the actual difficulties posed by current operations, Airmen must ensure that they do not neglect the theoretical basis of their profession and an understanding of what might be required of them in the future. Commendable efforts such as those undertaken by the Combined Air Power Transition Force in Afghanistan should be mirrored in the corridors of (air)power in coalition capitals and among the institutions, training establishments, and doctrine organizations that cultivate airpower at home. We have made steady and effective progress in the application of airpower in COIN operations over the past decade, but this has perhaps occurred in spite of associated conceptual efforts—not because of them. Hitherto, the military's post–Cold War transformation from an era of national defence to one of global security has focused on conducting defence within an expeditionary framework rather than adjusting to the repercussions of a newly defined threat. For instance, for various reasons (e.g., preparing for potential interstate conflict), the RAF may presently eschew procurement of a basic LAAR aircraft, but this may be precisely a capability that would produce significant dividends in prosecuting a COIN conflict and rapidly developing indigenous military capability. Such an aircraft might also have utility in other stability, low-intensity, or peacekeeping operations. We cannot avoid the implications of this shifting context by neglecting them. In both COIN operations and the potential crises awaiting the employment of airpower, Airmen face significant challenges to the traditional emphasis placed on kinetic capabilities, the primary role of airpower when opposing forces cannot effectively contest control of the air, and the potential consequences of operations amidst a civilian population. Fundamentally, we must explore and address these and related issues because they have implications not only for the tactical employment of air assets but also for future acquisition and capability requirements.

It is difficult to categorise the wars in Iraq and Afghanistan as a temporary trend. Their duration, the rise of nonstate actors as military antagonists, and the nearly global assimilation of technologies which enable such actors to threaten the interests of nation-states suggest that these conflicts represent more than a transient phase in warfare. Consequently, although it is essential that air forces remain capable of conducting both the range of missions and intensity of operations associated with conventional (interstate) warfare, if airpower is to optimise its contribution to the current campaign in Afghanistan and maintain its full relevance in the future, then it must also be effective beyond this traditional arena. Airmen, therefore, must ensure that airpower concepts and doctrine provide a proper foundation upon which to build. ✪

Notes

1. UK military doctrine uses the terms *moral*, *conceptual*, and *physical*. See Joint Doctrine Publication (JDP) 0-01, *British Defence Doctrine*, 3rd ed., August 2008, 4-1, http://www.mod.uk/NR/rdonlyres/CE5E85F2-DEEB-4694-B8DE-4148A4AEDF91/0/20100114jdp0_01_bddUDCDCIMAPPS.pdf.

2. Field Manual (FM) 3-24 / Marine Corps Warfighting Publication (MCWP) 3-33.5, *Counterinsurgency*, December 2006, http://usacac.army.mil/cac2/coin/repository/FM_3-24.pdf.

3. JDP 3-40, *Security and Stabilisation: The Military Contribution*, November 2009, http://www.mod.uk/NR/rdonlyres/C403A6C7-E72C-445E-8246-D11002D7A852/0/20091201jdp_40UDCDCIMAPPS.pdf; and British Army Field Manual, vol. 1 (AFM1), pt. 10, *Countering Insurgency*, January 2010, http://www2.armynet.mod.uk/linkedfilesANOpen/akx/coin_afm/20100408_afm_vol1_part10_jan2010ac71876-u.pdf.

4. JDP 3-40, *Security and Stabilisation*, 2-11; and AFM1, *Countering Insurgency*, 1-1.

5. The author is indebted to Col Alex Alderson of the British Army for his contribution to this point and others.

6. FM 3-24 / MCWP 3-33.5, *Counterinsurgency*, 5-18.

7. JDP 3-40, *Security and Stabilisation*, 4-20.

8. The author is indebted to Group Capt Dean Andrews, RAF, for his contribution to this point and others.

9. *Report on Progress toward Security and Stability in Afghanistan*, Report to Congress, November 2010, 12, http://www.defense.gov/pubs/November_1230_Report_FINAL.pdf.

10. *"Troops in Contact": Airstrikes and Civilian Deaths in Afghanistan* (New York: Human Rights Watch, September 2008), 13, http://www.hrw.org/sites/default/files/reports/afghanistan0908webwcover_0.pdf.

11. R. Chuck Mason, *Status of Forces Agreement (SOFA): What Is It, and How Has It Been Utilized?*, CRS Report RL34531 (Washington, DC: Congressional Research Service, 18 June 2009), 9, http://www.fas.org/sgp/crs/natsec/RL34531.pdf; "Afghan Senate Protests Civilian Deaths," PRI's the World, 16 September 2008, http://www.pri.org/theworld/?q=node/21011; and "Controversial Airstrike in Afghanistan: A Chronology," Deutsche Welle, DW-World.DE, 27 November 2009, http://www.dw-world.de/dw/article/0,,4934122,00.html.

12. See Brig Gen Michael R. Boera, "The Combined Air Power Transition Force: Building Airpower for Afghanistan," *Air and Space Power Journal* 24, no. 1 (Spring 2010): 16–26, http://www.airpower.au.af.mil/airchronicles/apj/apj10/spr10/aspj_en_2010_1.pdf.

13. AFM1, *Countering Insurgency*, chap. 9, sec. 2; FM 3-24 / MCWP 3-33.5, *Counterinsurgency*, annex E; and JDP 3-40, *Security and Stabilisation*, xxv.

14. Sgt Sarah Wood, American Forces Press Service, "Petraeus Supports Troop Increase in Confirmation Hearing," Operation New Dawn, Official Website of United States Forces–Iraq, 24 January 2007, accessed 15 December 2010, http://www.usf-iraq.com/news/headlines/petraeus-supports-troop-increase-in-confirmation-hearing.

Paul Smyth

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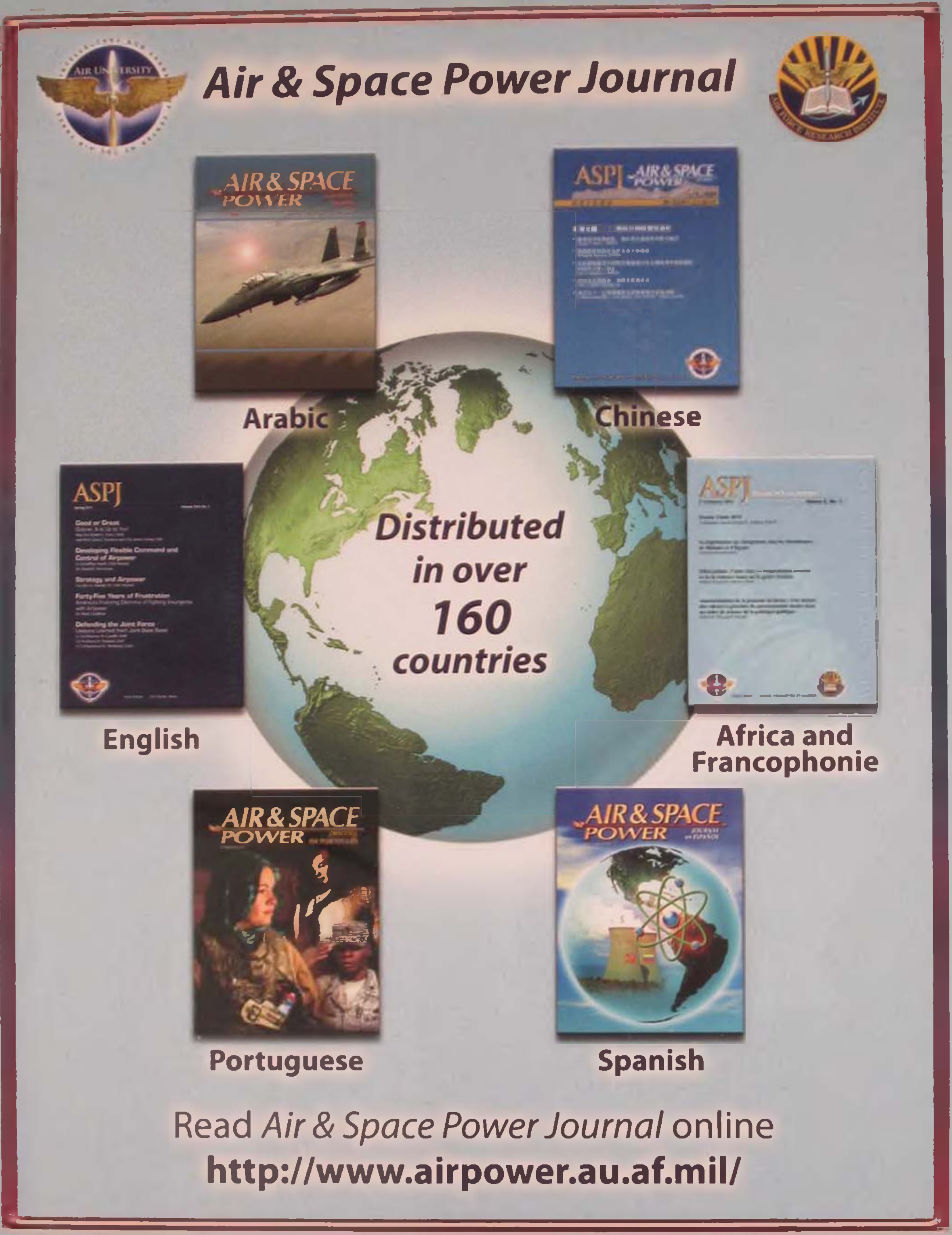

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