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

Maj Kenneth A. Fisher, PhD, USAF
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-

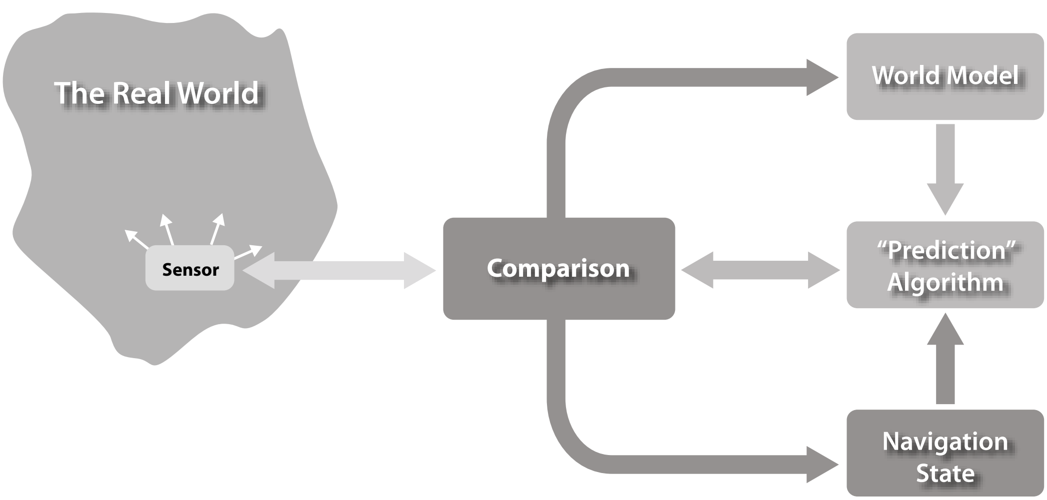

Figure 1. Notional navigation algorithm

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

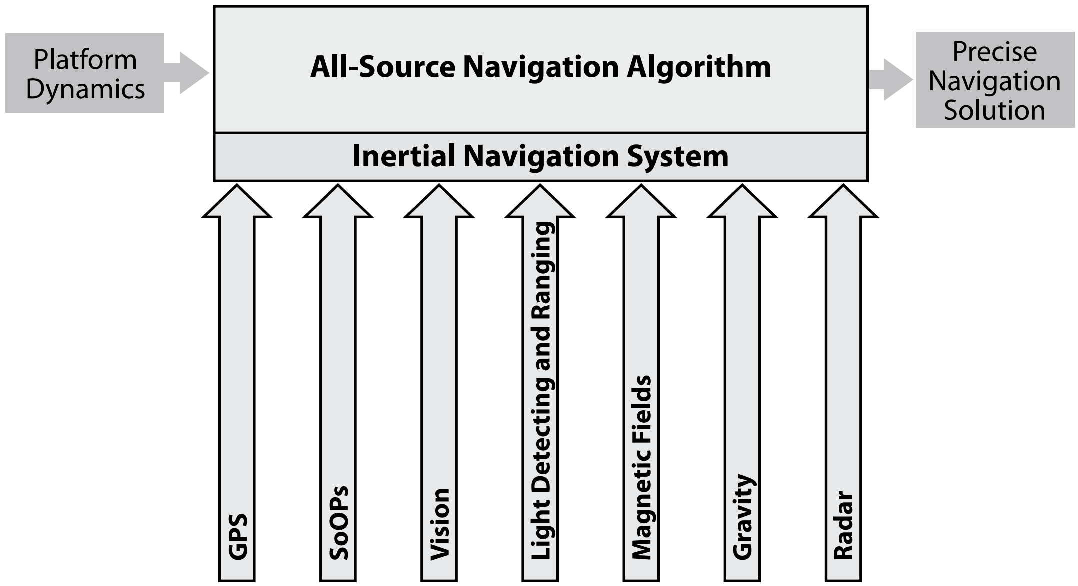

Figure 2. Notional all-source navigation algorithm

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. ✪

Wright-Patterson AFB, Ohio

Notes

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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.

7. The filter is named after Rudolph Kalman, who first published his predict-observe-compare algorithm in "A New Approach to Linear Filtering and Prediction Problems," *Transactions of the ASME* [American Society of Mechanical Engineers]—*Journal of Basic Engineering* 82 (1960): 35–45, http://www.cs.unc.edu/~welch/kalman/media/pdf/Kalman1960.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).

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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).

21. Raytheon provides the radio communication system for the Land Warrior program currently operating with the 4th Stryker Brigade Combat Team in Iraq. The ANT Center and Raytheon operate through a cooperative research and development agreement to develop non-GPS navigation solutions.

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.

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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 motorglider 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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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.[13] 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.

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Jet Propellant 8 versus Alternative Jet Fuels

A Life-Cycle Perspective

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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-

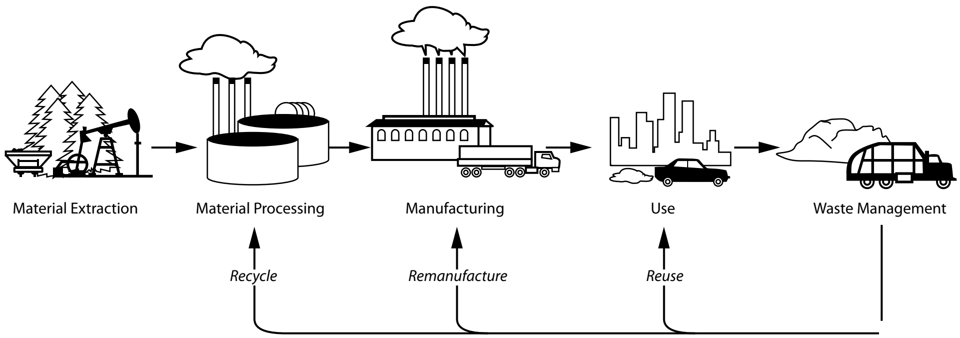

Figure 1. Life-cycle assessment phases. (Reprinted from Congress of the United States, Office of Technology Assessment, *Green Products by Design: Choices for a Cleaner Environment* [Washington, DC: Congress of the United States, Office of Technology Assessment, September 1992], 4.)

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

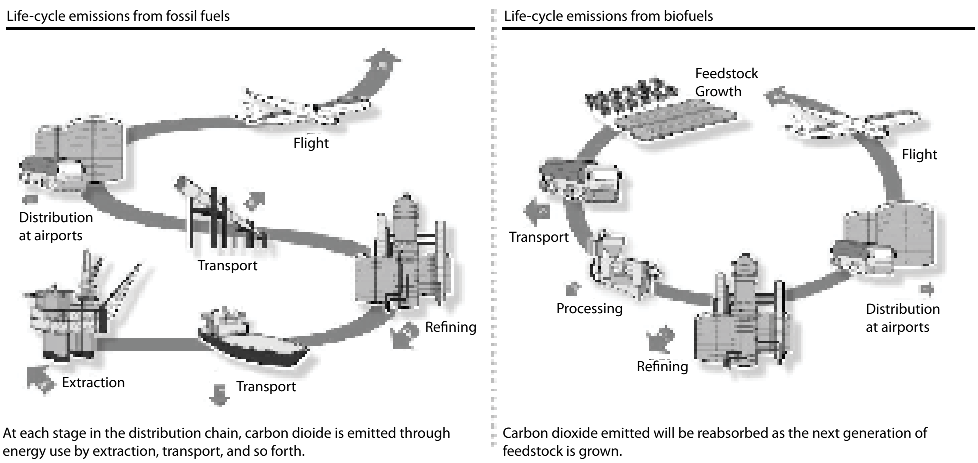

Figure 2. Life-cycle CO_2 emissions. (Reprinted by permission from Air Transport Action Group, *Beginner's Guide to Aviation Biofuels* [Geneva, Switzerland: Air Transport Action Group, May 2009], 3, http://www.enviro.aero/Content/Upload/File/BeginnersGuide_Biofuels_WebRes.pdf.)

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,

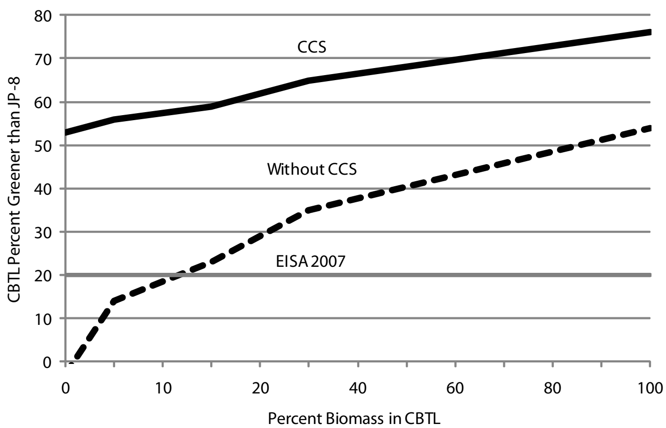

Figure 3. Percent biomass in CBTL versus CBTL percent greener than JP-8

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. ✪

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Using Nanotechnology to Detect Nerve Agents

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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

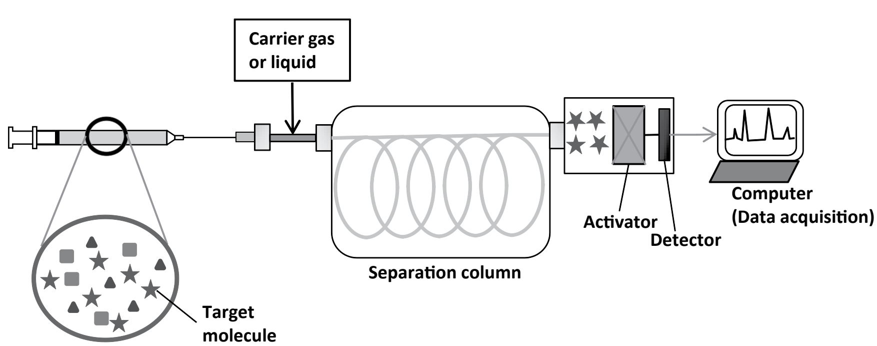

Figure 1. Schematic description of a typical gas chromatography detection system

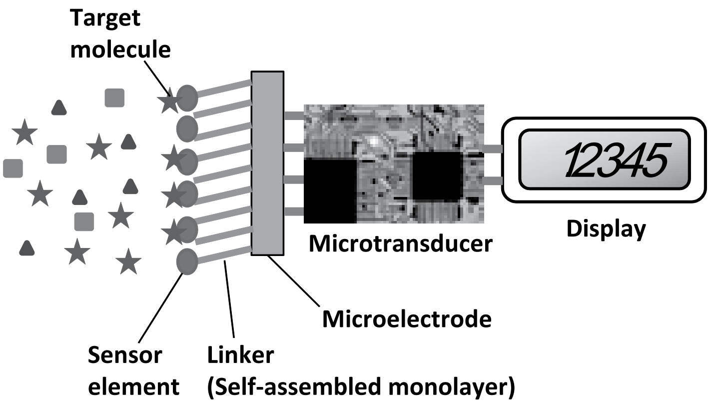

Figure 2. Schematic description of a nanosensor system on a microchip

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.

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.

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-

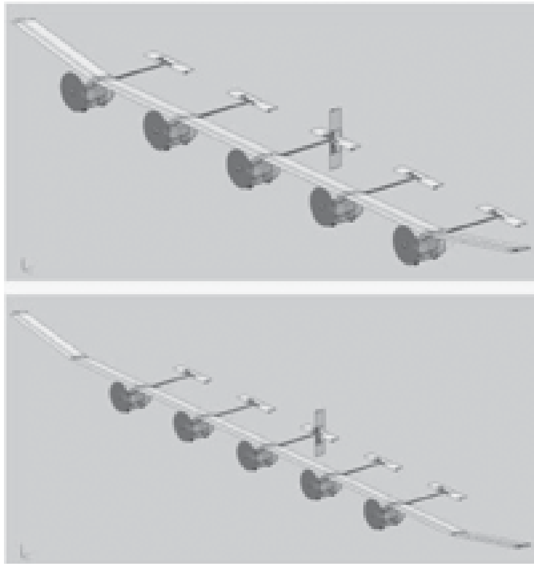

Figure. X-HALE six- (above) and eight-meter (below) wingspan designs

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

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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.

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Aerospike Rockets for Increased Space Launch Capability

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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-

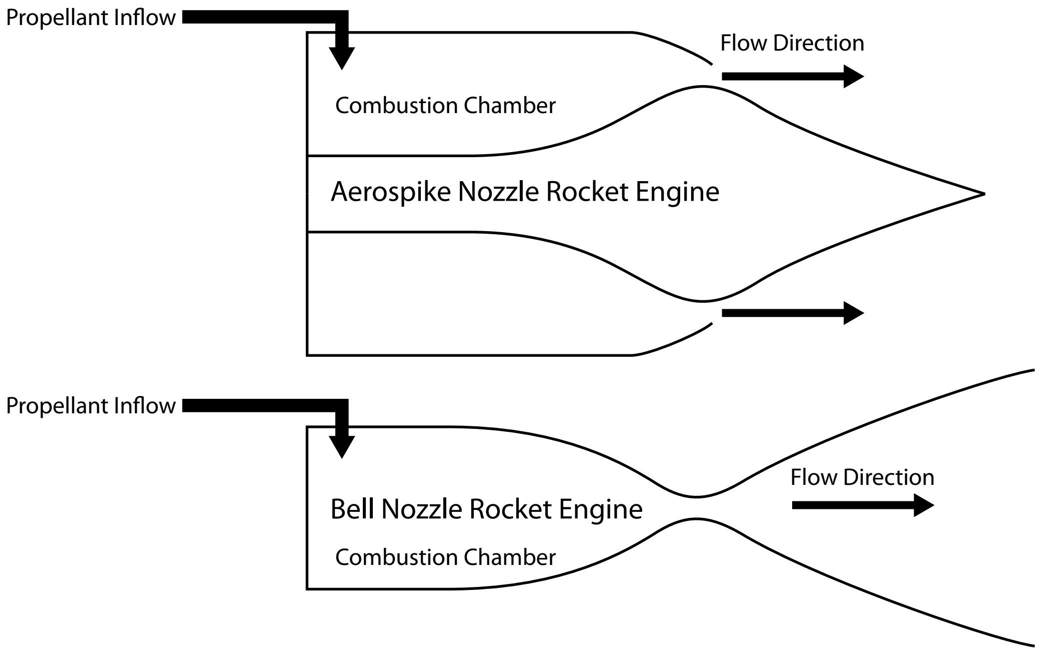

Figure 1. Geometry of aerospike and bell-nozzle rocket engines

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,

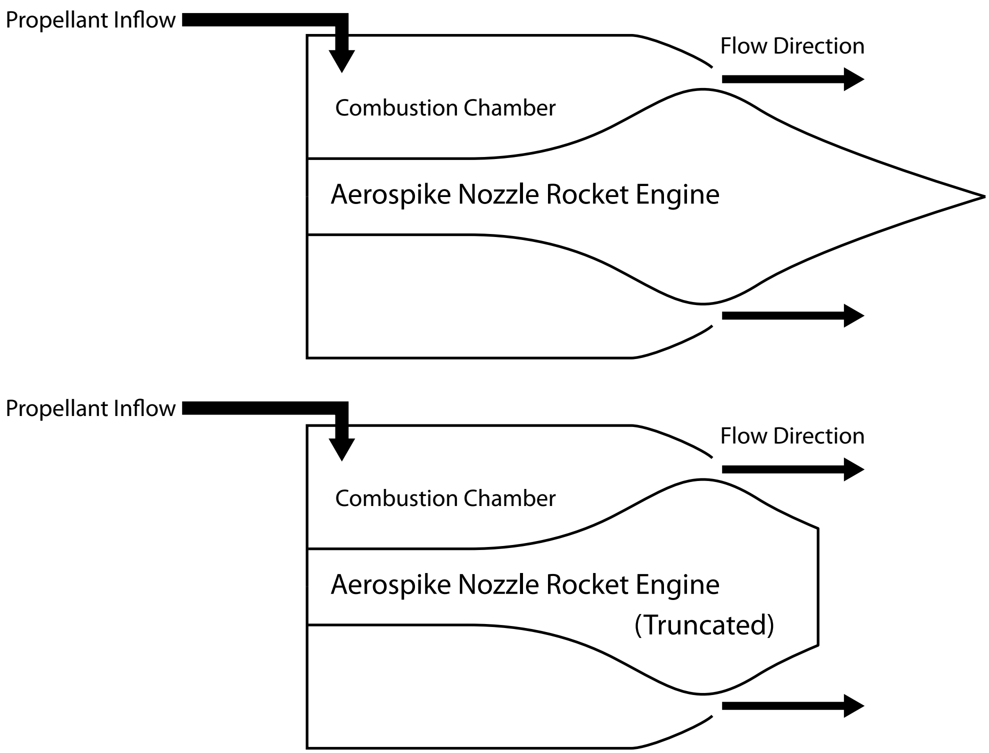

Figure 2. Geometry of truncated and nontruncated aerospike engines

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

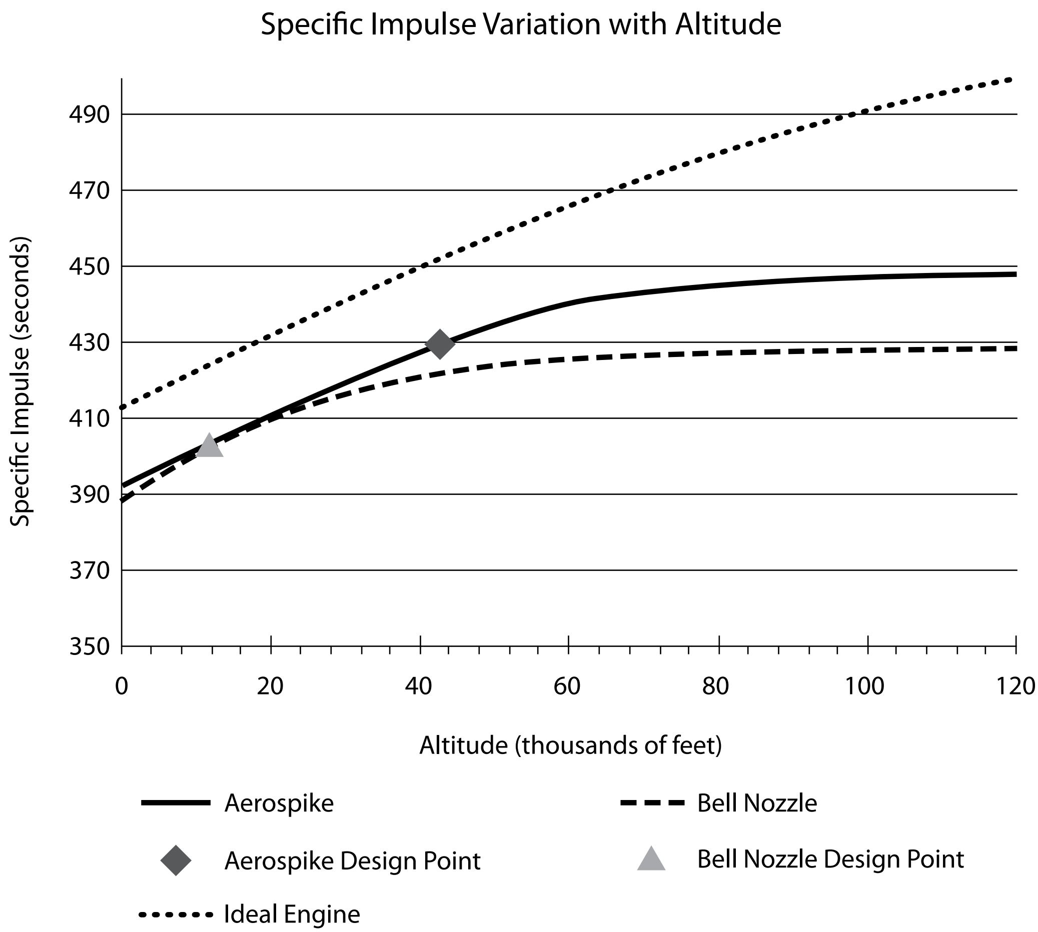

Figure 3. Performance advantage of aerospike engines in the atmosphere

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
Dr. Jonathan T. Black*

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 per-forms 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/halleffect.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.