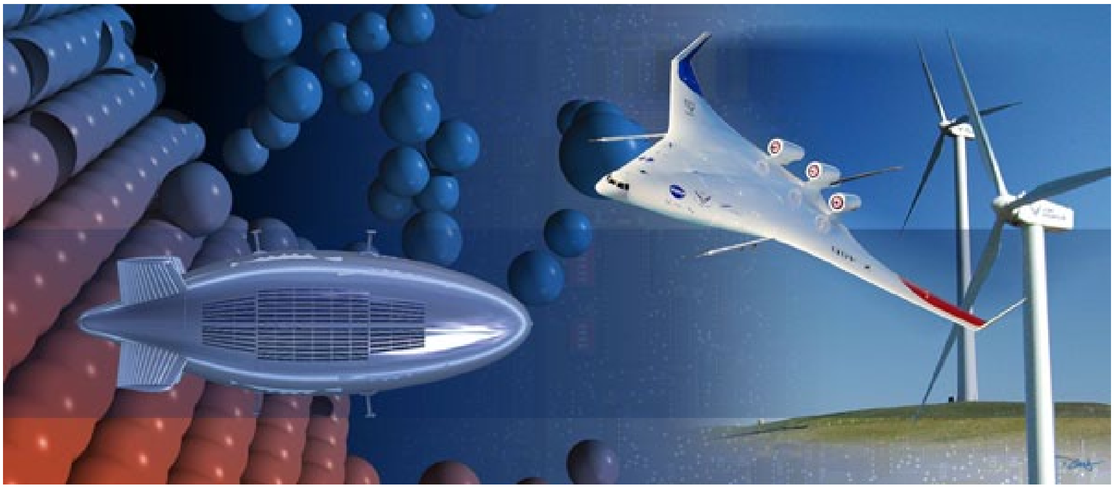
Energy Horizons

A Science and Technology Vision for Air Force Energy

Dr. Mark T. Maybury



Introduction and Vision

The Air Force faces daunting energy challenges that promise only to increase in severity, given the increased global demand for energy, diminishing global energy supplies, and demands for enhanced environmental stewardship. The service spends over $9 billion a year in aviation fuels and over $100 million annually in energy for ground operations associated with space, and tens of millions of dollars in cyber energy to support command and intelligence centers. (Figure 1 shows the proportional share of operational energy.) Adversaries increasingly target energy as a center of gravity. To date, more than 3,000 American Soldiers and contractors have been killed or wounded protecting supply convoys in Iraq and Afghanistan (approximately one life per 30 convoys), 80 percent of which transported primarily water and fuel.

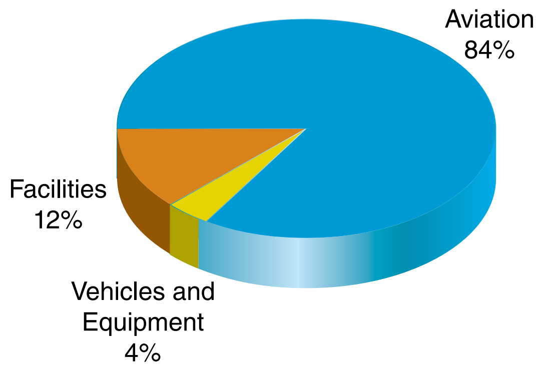


Figure 1. Cost breakdown of Air Force energy, fiscal year (FY) 2010. (Adapted from Headquarters US Air Force, *Air Force Energy Plan 2010* [Washington, DC: Headquarters US Air Force, 2010], 4, http://www.dm.af.mil/shared/media/document/AFD-101202-066.pdf.)

The Air Force report titled *Energy Horizons: A Science and Technology Vision for Air Force Energy, 2011–2026* is informed by the Department of Defense's (DOD) *Energy for the Warfighter: Operational Energy Strategy*; the *Air Force Energy Plan 2010*; and the *National Aeronautics Research and Development Plan*.[1] The Air Force's energy vision seeks to "make energy a consideration in all we do," including understanding "how energy impacts the Air Force's critical capabilities: Global Vigilance, Global Reach, and Global Power."[2] Furthermore, the *Energy Horizons* report offers a vision of "assured energy advantage across air, space, cyberspace and infrastructure."[3]

Air Energy

The Air Force is the single largest energy user in the DOD. The service uses more than 2 billion gallons of aviation fuel every year, making it the predominant form (84 percent) of energy consumed and creating one of the Air Force's largest operational expenses. Operational improvements to new platforms such as the C-17 and F-35 come with burn rates 50 percent to 125 percent more than those of legacy platforms such as the C-141 and F-16.[4] Figure 2, representing mobility air forces, combat air forces, and special air forces, depicts the projected fuel burn of the Air Force through 2040.

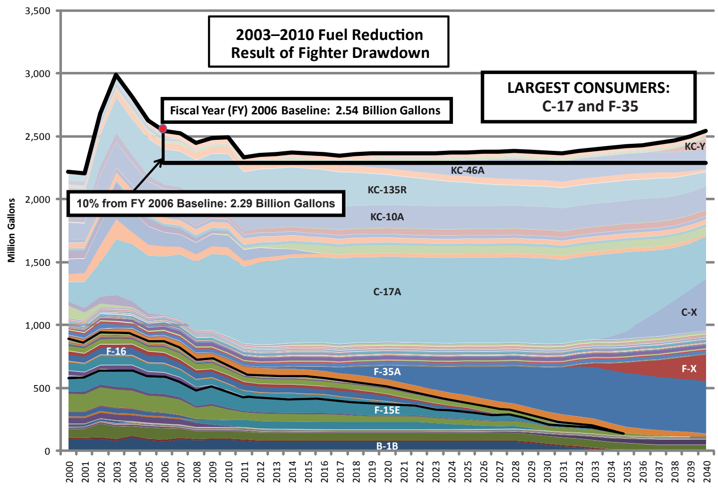


Figure 2. Air Force fuel-burn projections. (From Dr. Jackie Henningsen, AF/A9, director, Studies and Analyses, Assessments and Lessons Learned.)

In the air domain, the Breguet range equation provides a unifying method for simultaneously measuring the progress of energy efficiency, related energy use, and aircraft capabilities:[5]

$$Range = \frac{V}{SFC}\frac{L}{D}\ln\left(1 + \frac{W_{fuel}}{W_{payload} + W_{aircraft}}\right)$$

In this equation, one can measure improvements to airframe efficiency via increases to the lift-to-drag (L/D) coefficient and reductions in weight of the aircraft ($W_{payload}$ + $W_{aircraft}$). Further, one can measure efficiency gains in propulsion via the specific fuel consumption (SFC) relative to the speed (V). Linking energy to range across these factors establishes a relationship between war-fighter capability and energy-efficiency attributes. Science and technology (S&T) investments in the air domain seek to optimize one or more pertinent elements of the Breguet equation (table 1). These include advancements in aerodynamics, propulsion and power, materials and structures, aviation operations, energy harvesting, and game-changing concepts. Table 1 articulates where the Air Force needs to lead (L); where it should follow (F) by rapidly adopting, adapting, or augmenting the investments of others; and where it should watch (W) investments (other than core mission functions) that it depends upon.

Table 1. Air-energy science and technology

<table>
<tr><th></th><th>Near (FY 11–15)</th><th>Mid (FY 16–20)</th><th>Far (FY 21–25)</th></tr>
<tr><td rowspan="8">Aerodynamics</td><td>Fairings (L)</td><td>Conformal Antennas (F)</td><td>Laminar Flow (Combat Fleet) (L)</td></tr>
<tr><td>Center of Gravity Control (L)</td><td>Laminar Flow (Mobility Fleet) (F)</td><td></td></tr>
<tr><td>Lift Distribution Control (L)</td><td>Systems Integration (F) (Mobility Fleet)</td><td></td></tr>
<tr><td>Winglets, Finlets, Strakes (F)</td><td colspan="2">Systems Integration (F) (Combat Fleet)</td></tr>
<tr><td>Raked Wings (F)</td><td colspan="2">Blended Wing Body (F)</td></tr>
<tr><td>Microvanes (F)</td><td colspan="2">X-Wing (F)</td></tr>
<tr><td></td><td colspan="2">Lifting Bodies (W)</td></tr>
<tr><td colspan="2"></td><td>Plasma-Enhanced Drag Reduction (W)</td></tr>
<tr><td rowspan="10">Propulsion & Power Systems</td><td>Adaptive Versatile Engine Technology (L)</td><td>Highly Efficient Embedded Turbine Engine (L)</td><td>Advanced and Nutating Cycles (L)</td></tr>
<tr><td>Efficient Small-Scale Propulsion (L)</td><td>Engine-Specific Improvements (L)</td><td>Turbofan Compounding (W)</td></tr>
<tr><td>Heavy Fuel (F)</td><td>Subsystem Integration (L)</td><td>Ultrahigh Bypass (W)</td></tr>
<tr><td>Geared Turbofan (F)</td><td>Power on Demand (F) (Mobility Fleet)</td><td></td></tr>
<tr><td></td><td>Power on Demand (L) (Combat Fleet)</td><td></td></tr>
<tr><td></td><td>Open-Rotor Engine (W)</td><td></td></tr>
<tr><td></td><td>Hybrids/Electric Propulsion (W)</td><td></td></tr>
<tr><td colspan="2">Alternative and Biomass Fuels Qualification/Certification (L)</td><td></td></tr>
<tr><td colspan="2">Alternative and Biomass Fuels Production (W)</td><td></td></tr>
<tr><td></td><td colspan="2">Advanced Power Generation (F)</td></tr>
<tr><td rowspan="6">Materials & Structures</td><td>Aircraft Components (Tie-Downs, Pallets, Racks) (L)</td><td colspan="2">Multifunctional Materials (F)</td></tr>
<tr><td>Lighting (F)</td><td>Wireless Control Systems and Electric Actuators (W)</td><td></td></tr>
<tr><td colspan="2">Composite Materials (L)</td><td></td></tr>
<tr><td colspan="2">Composite Cargo Containers (F)</td><td></td></tr>
<tr><td colspan="2">Morphing Materials (F)</td><td></td></tr>
<tr><td colspan="2">Hybrids/Advanced Aluminums (F)</td><td></td></tr>
<tr><td rowspan="8">Aviation Operations</td><td>Formation Flight (L)</td><td colspan="2">Sustainment Improvements (L)</td></tr>
<tr><td>Mission Index Flying (F)</td><td></td><td></td></tr>
<tr><td colspan="2">Distributed Mission Training and Interactive Simulators (L)</td><td></td></tr>
<tr><td colspan="2">Improved Human Performance Considerations (L)</td><td></td></tr>
<tr><td colspan="2">Expansion of Remotely Piloted Aircraft (RPA) Role in Mission (L)</td><td></td></tr>
<tr><td colspan="2">Improved Weather Forecasting, Detection, Avoidance (F)</td><td></td></tr>
<tr><td colspan="2">Enhanced Mission-Execution Efficiency Practices (F)</td><td></td></tr>
<tr><td colspan="3">Mission-Planning Software (F)</td></tr>
<tr><td rowspan="6">Energy Harvesting</td><td colspan="2">Thermoelectric for Cooling (L)</td><td></td></tr>
<tr><td></td><td colspan="2">Energy Harvesting for Small RPAs (L)</td></tr>
<tr><td>Photovoltaics (F)</td><td>Magnetic Braking (F)</td><td></td></tr>
<tr><td colspan="2">Thermoelectric Exhaust Recapture (F)</td><td></td></tr>
<tr><td colspan="2">General Thermoelectric Reclamation (F)</td><td></td></tr>
<tr><td></td><td colspan="2">Acoustics (W)</td></tr>
<tr><td>New</td><td></td><td>Hybrid Airships (F)</td><td>Fractionated Systems (L)</td></tr>
</table>

Aerodynamics

Improvements in aerodynamics for both the legacy and future fleets illustrated in the first section of table 1 include finlets, winglets, riblets, and conformal antennas among other streamlining modifications, offering 4–6 percent better fuel burn. Similarly, center of gravity controls and lift-distribution control systems enhance performance by ensuring that lift is efficiently appropriated across the aircraft in relation to the location of the carried weight. Midterm and far-term considerations include wings optimized for laminar flow (up to 15 percent fuel savings) and nontraditional airframes (e.g., blended-wing [see fig. 3], box-wing, and lifting-body constructions).

Figure 3. X-48B blended-wing body. (From NASA Dryden Flight Research Center Photo Collection, 14 August 2007, http://www.dfrc.nasa.gov/Gallery/Photo/X-48B/Medium/ED07-0192-08.jpg.)

Propulsion and Power Systems

Propulsion technologies offer potential fuel-burn reductions across a variety of platforms, as expressed in the second section of table 1. The Air Force will lead many of the technologies listed or act as a fast follower for future commercial off-the-shelf solutions. For example, Adaptive Versatile Engine Technology (ADVENT) (see fig. 4) has improved compressors and a third flow that potentially would provide significant energy savings (15–25 percent reduction in SFC) to combat aircraft. Moreover, the Highly Efficient Embedded Turbine Engine could improve the SFC of mobility and other platforms by 25 percent. Moving beyond conventional Brayton cycle (air-breathing) concepts, revolutionary midterm and far-term technologies aim for high efficiency, such as hybrid pressure-gain combustion cycles, hybrid turbocompound cycles, heat-exchange cycles (intercooled and regenerative), interturbine burning leading to isothermal expansion cycles, and positive-displacement compression cores. For smaller aircraft, initiatives like Efficient Small-Scale Propulsion look to provide an approximately 25 percent reduction in SFC, in this case for remotely piloted aircraft (RPA). Its fleet fully certified for 50/50 Fischer-Tropsch/JP-8, the Air Force will lead continued fleet qualification/certification of new, sustainable feedstocks. The service will closely watch and leverage biofuels production, given an existing joint Department of Energy / Agriculture / Navy program in biofuel production.

Figure 4. ADVENT. (From Briefing, subject: Introduction to Air Force Research Laboratory Propulsion Directorate, slide 8, accessed 26 January 2012, http://www.wpafb.af.mil/shared/media/document/AFD-080429-021.pdf.)

Materials and Structures

As detailed in the third section of table 1, materials research in composites and carbon nanotubes promises enhancements in aircraft structure and cargo container properties such as reduced weight, tensile strength, conductivity, thermal management, and energy storage, contributing to reduced fuel burn. Improved materials can sometimes also lead to cheaper production, a significant reduction in parts (e.g., fasteners), lower maintenance costs, and minimal sustainment footprint in forward-deployed areas. Other weight-reduction technologies include wireless control systems, electric (rather than hydraulic) actuators, light-emitting diodes, and synthetic tie-downs to replace hefty chains. Further, the flexibility in composite and morphing materials holds potential for allowing certain aircraft parts—such as winglets or vortex generators—to self-adjust, based on airstreams and aircraft angles of attack, producing better fuel-burn characteristics. In the mid-term to far term, multifunctional materials offer exciting possibilities for advanced energy harvesting to reduce energy lost as heat or noise.

Aviation Operations

Aviation operations, reflected in section four of table 1, offer efficiency gains with comparatively low up-front costs. For instance, experiments with C-17s' flight formation (fig. 5) have demonstrated 5–10 percent fuel savings for trailing aircraft with limited impact on aircrews, structural considerations, or scheduling. Further, following the lead of commercial airlines, the Air Force implemented mission index flying to optimize options for cruise flight levels and speeds as well as climb and descent profiles tailored to flight conditions. Maximizing distributed, interactive flight simulators (e.g., linking KC-135 and F-16 simulators) can not only decrease the training costs of live operations but also enable safe training in contested or congested conditions, thus enhancing readiness. Improved planning software that is more aware of mission elements, real-time weather, and mission requirements can reduce sorties and inefficient route planning. Additionally, future RPAs and autonomous aircraft could be tailored to specific mobility and combat missions currently carried out by traditional aircraft and do so with a reduced total-energy footprint. Finally, optimizing mission planning and aircraft basing so as to place airframes with lower maintenance requirements in forward locations lowers the cost of second-order effects (e.g., fewer parts forward).

Figure 5. Formation flying. (From Kenji Thuloweit, "Formation Flight System Keeps C-17s in Line," 95th Air Base Wing Public Affairs, Edwards AFB, CA, 22 September 2010, http://www.edwards.af.mil/news/story.asp?id=123223228. See also "C-17 Multiple Ship Formation Flight Test at Edwards AFB," video, YouTube, 18 September 2010, http://www.youtube.com/watch?v=jBvua6nptsE.)

Energy Harvesting

Section five of table 1 shows that Air Force S&T could combine thermoelectric conversion with other energy-capture concepts such as acoustic/vibration and energy recovery from magnetic braking. The latter might reduce maintenance costs and system weight as well as capture braking energy for reuse in taxiing. Future energy-omnivorous aircraft could possibly harvest a host of energy inputs, including multifuel, solar, heat, wind, and vibration to reduce or perhaps eliminate their demand on traditional fuel. For small RPAs, novel concepts such as recharging those aircraft while perching or harvesting power from thermal or electric sources could enable continuous autonomous operations. The area of energy harvesting could transform many of our operations; however, challenges such as design, power density, system integration, and cost demand attention.

Game-Changing Concepts

The final section of table 1 notes alternative concepts that depart from the traditional airframe. In the midterm, hybrid airships (fig. 6) exploit both the buoyancy of gas (typically helium) in their envelope and aerodynamic lift produced by airflow over the airships' large surface area. Daunting operational issues remain, such as ground handling, avoidance of bad weather, buoyancy control, and infrastructure, but the projected cost per pound of cargo moved is significantly less than that of traditional airlift. High-altitude airships also have applications for intelligence, surveillance, and reconnaissance (ISR). Furthermore, fractionated systems—which can be decomposed and recomposed, based on mission requirements—promise more efficient ISR, mobility, and swarming attack.

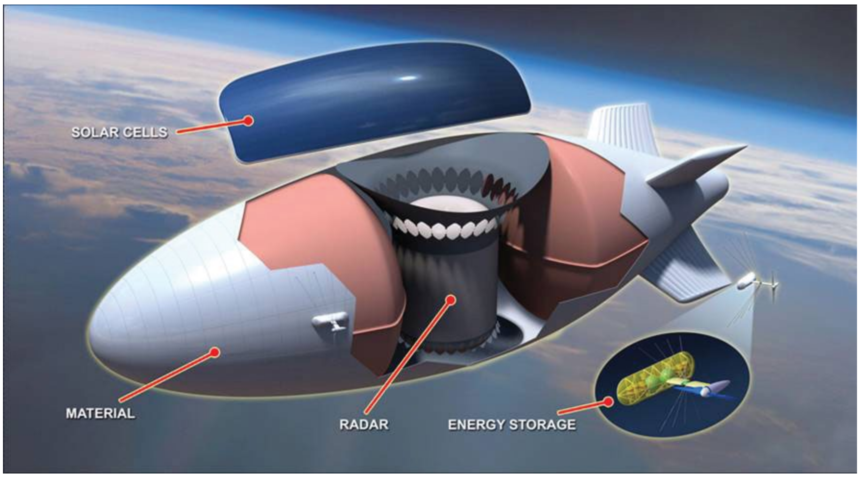


Figure 6. Sensing airship. (From "Integrated Sensor Is Structure [ISIS]," Strategic Technology Office, Defense Advanced Research Projects Agency, accessed 26 January 2012, http://www.darpa.mil/Our_Work/STO/Programs/Integrated_Sensor_is_Structure_(ISIS).aspx.)

Space Energy

In contrast to assets in the air domain, those in the space portfolio do not use traditional aviation fuels for mobility (airlift and air refueling). Indeed, once space assets reach orbit—with the very small exception of onboard consumables (e.g., propulsion for satellite maneuverability)—the primary energy expense arises from the operation of associated ground-control and data-processing facilities (over $100 million annually). Of the energy consumed for Air Force Space Command's missions, terrestrial facilities use 97.2 percent, ground-vehicle transportation uses 1.8 percent, and rocket launches account for an estimated 1 percent. Commercial space systems operate with smaller facilities, small crews, and even autonomously. Terrestrial radar and heating, ventilation, and air conditioning (HVAC) systems present another underrealized opportunity for reductions in the cost of energy. Additionally, several technologies hold promise for energy generation, storage, and transmission in support of space operations (table 2).

Table 2. Space energy science and technology

	Near (FY 11–15)	Mid (FY 16–20)	Far (FY 21–25)
Energy Generation	30–35% Efficient Photovoltaic (PV) Cells (L)	40% Evolved PV Cells (L)	70% Efficient PV Cells (e.g., Quantum Dots) (L)
	High-Power Solar Array/Integrated Blanket Interconnect System (L)	Sunshine to Petrol (F)	
		Space Nuclear Power for Orbital Systems (F) and Small Modular Nuclear for Ground Stations (F)	
Energy Storage	Flywheels for Space systems (L)	Nanomaterials for High-Power, High-Density Storage (F)	
	Domestic Lithium-Ion Batteries for Space Applications (F)		
	Facility Scale Energy Storage (F)		
Propulsion and Power	Highly Efficient Microprocessors (F)	Photonic Computing for Space Applications (F)	Quantum Computing (F)
	Efficient Orbital Thrusters (L)	Efficient Hall and Electric Thrusters (L)	Electromagnetic Propulsion (L)
		On-Orbit Satellite Refueling (L)	Electric Thrusters Powered by Local PV or Beamed Energy Systems (L)
Operations	Energy-Efficient Data Centers and Ground Stations (F), Cloud Computing (F)	Conversion of Terrestrial Base Use to Efficient Solar Energy (F)	Autonomous "Lights Out" Ground Operations (F)
	Adoption of Commercial Best Practices (F)	Development of Greater Autonomous Capabilities for Satellites (L)	Advanced Onboard Autonomy (F)
		Cross-Domain Study for Space Functionality (L)	Fractionated, Space-to-Space Power-Beamed Energy Constellations (L)
	Improvements to Efficient Launch-Booster Technology (F)	Investigation of Reusable Boost System Concept (F)	Revolutionary Small Launch/Midlaunch, Including Air-Launched Capability for Small Satellites (L)

Energy Generation

The first section of table 2 addresses the generation of space energy, emphasizing high-efficiency and high-power photoelectric power, sun-to-petrol, and nuclear power. Current solar efficiencies range from 10 percent for flexible, amorphous silicon, to 34 percent for inverted metamorphic solar cell arrays, to (theoretically) as much as 70 percent with quantum dots and diluted nitrides in the far term. The importance of these S&T efforts lies in the fact that every 1 percent in the efficiency of solar-cell energy generation translates to a 3.5 percent increase in power (or decrease in mass) for the system. Very large deployable panels include the Air Force Research Laboratory (AFRL)–Boeing 30-kilowatt (kW) Integrated Blanket Interconnect System High Power Solar Arrays. In the midterm to far term, sunshine-to-petrol is a prototype funded by the Department of Energy to convert carbon dioxide (CO_2) and water (H_2O) into carbon monoxide (CO) and hydrogen (H_2) to create liquid fuel. In addition, 500 kW of on-orbit power could enable space-based sensing and power beaming missions. Entirely new technologies include tethers to attempt to harvest energy from the geomagnetic field and energy harvesting from a system's heat waste. Several satellite systems (e.g., radioisotope thermoelectric generators) have already demonstrated the use of nuclear energy. Moreover, modern designs exist for buried, autosafing, waste-consuming small modular nuclear reactors for assured ground-operations energy.

Energy Storage

The second section of table 2 considers energy storage. Because of discontinuation of the Teflon-30 nickel-hydrogen (Ni:H) separator material in Ni:H batteries after 2012 in response to environmental concerns, research to develop an accelerated life test for lithium-ion chemistries will become important for future national space-security missions. In the near term, storage technologies such as flywheels could provide the required energy with the added feature of reaction wheels, having the potential to assist with attitude control. In the longer term, advances in nanomaterials promise high-power, high-density storage; high-cycling and discharge rates; and increased battery lifetime. In contrast, ground stations and data centers can leverage hybrid technologies, including traditional lead-acid batteries and large flywheels.

Propulsion and Power

The third section of table 2 considers propulsion and power in space. On-orbit systems such as sensors, communications equipment, and onboard processing require intense amounts of power.

Beyond near-term efficient microprocessors, innovations such as memristors, photonic computing, and quantum computing could produce significant energy efficiencies (further addressed in the "Cyber Energy" section, below). Advantages include smaller size and greatly reduced thermal load beyond silicon alternatives.

Advances in satellite propulsion are also essential for orbit raising, station keeping, and maneuver, particularly for low-Earth-orbiting satellites. In the midterm, the survivability and increased longevity of current-generation satellite systems demand further investigation. In the midterm and far term, technologies such as Hall and electric thrusters may lead to extended utility of limited onboard propellants. Concepts for on-orbit satellite refueling that leverages power beaming similarly promise to extend mission life. In the far term, advanced concepts in electromagnetic propulsion can provide advantages in mission duration and resiliency. Utilizing onboard power harvested from the environment, these systems can extend space maneuver without propellant, offering more weight and volume for operational capability.

Operational Innovations

As in the air domain, new methods of operation shown in section four of table 2 may generate significant savings. Given the fact that terrestrial systems consume 97 percent of the power for space operations, in the near term, a commercial data center's best practices in HVAC and power management as well as cloud computing should be adopted, as detailed in the "Cyber Energy" and "Infrastructure Energy" sections, below. The top legacy candidates include launch ranges, control stations, data-processing centers, and ground-based space radar (fig. 7). In the midterm to far term, increased autonomy will decrease the need for operators and associated energy. Renewable energies are viable options for reducing the energy footprint of these facilities and assuring energy independence. Despite the many challenges in power beaming from space to earth, in the long term, space-to-space energy beaming could enable "fractionated" satellites, which are not only smaller but also more capable, distributed, and survivable than current systems. Also important are multidomain analyses to examine the relative energy efficiency of performing missions in the air and in space. Finally, increasing the efficiency of launch boosters will enhance access to space.

Figure 7. PAVE PAWS Radar. (From "PAVE PAWS FAQS," Peterson Air Force Base, 30 September 2010, http://www.peterson.af.mil/library/factsheets/factsheet.asp?id=10506.)

Cyber Energy

All Air Force missions depend upon cyber infrastructures, especially the energy infrastructure itself. This dependency will increase as the service advances autonomous systems linked to each other and to service members through cyberspace to deliver more capability at less cost. Protecting our air and space missions as they traverse cyberspace for purposes of command and control, communications, ISR, or putting weapons on target is essential for power projection over global distances to ensure the Air Force vision of "Global Vigilance, Global Reach, Global Power." Adversaries will attempt to deny, degrade, manipulate, disrupt, or destroy critical infrastructures through cyberspace attack to undermine vital missions.

While device size, weight, and energy consumption drops, problems associated with compact energy storage rise. Over the past 15 years, floating point operations per second (flops) per kW have improved 700-fold, from 2.5 billion to 1,945 billion flops/kW. We envision that this trend of doubling power efficiency every 1.6 years will continue through 2020, allowing high-performance computing (HPC) system-level power efficiencies to exceed 100 billion flops/W. This will greatly improve the capacity of data centers.[6] It will also allow more sophisticated processing within embedded systems in the field.

One important metric for cyber energy—power usage effectiveness (PUE), equal to total facility power divided by information technology equipment power—measures how much additional power the infrastructure consumes over and above the servers themselves. For example, if for every watt consumed by the server, the infrastructure consumes another half watt, the PUE is 1.5. Current state-of-the-art commercial enterprises operate at PUEs of 1.2.

The Air Force vision for cyber energy encompasses four areas: empowering the mission, optimizing human/machine systems, enhancing agility and resilience, and inventing new foundations (table 3).

Table 3. Cyber energy science and technology

Thrust	Area	Near (FY 11–15)	Mid (FY 16–20)	Far (FY 21–25)
Empowering the Mission	System Efficiencies	• Algorithm/Code/Hardware Efficiencies (L) • Hardware Architecture (3-D Chips) (e.g., Memory on Memory) (L) • Efficient Software Architectures (L) • SWAP (Size/Weight/Power)-Efficient Computer Technology (F) • Energy-Efficient HPC Resource Control (W) • Lightweight Hardware (W)	• Nanosensor Development; Nanoprocessing Technology (L) • Integrated Optical Single-Photon Quantum Key Distribution/ Processing on a Chip (L) • Processor Energy Optimization (F) • Optimization of Computer Power Supplies (F) • Environmental Adaptive Computing (W) • Intelligent HPC Resource Control (W) • Optimization of Computer Power Supplies SWAP-Efficient Computer Technology (W)	• Hardware Architecture Advances (3-D Chips) (L) • Quantum Computing Technology (F) • Memristor-Based Neuromorphic Circuits for Efficient Cognitive Computing (F) • SWAP-Efficient Computing Nanostructures (F)
	Renewables	• Nanotechnology-Based Architecture (F) • Alternative Power Supplies on Chip (Batteries, Supercapacitors, etc.) (W)	• Renewable-Powered (e.g., Solar) Small Computing Systems (W) • Alternative Energy Supplies (Solar, Wind, Geothermal) (W)	• Miniature Energy-Harvesting Systems for Micro RPAs (F)
Human/ Machine	Culture Issues	• Leadership Mandates (L) • Cultural/Behavioral Changes on Energy Efficiency (L) • Metrics, Data Consistency, and Measurement (F)	• Human Trust in Cyber (L) • Sensing and Augmentation of Human Performance (L) • Server Migration (Footprint) (F)	• Trust in Collective Teams of Humans and Machines (L)
Enhancing Agility and Resilience	Electricity	• Establishment of Policy/ Procedures in Energy Savings (L) • Monitoring and Control Systems (F) • Smart Grid (F)	• Alternative Energy (Solar Cell, Fuel Cells, etc.) (W) • Green Buildings (W) • Secure Smart Grid (F)	• Remote Measurements and Control Systems (Central Command for Energy) (F) • Robust, Secure, Smart Grid (W)
	Cloud Computing	• Efficient Computing Algorithms (L) • Heterogeneous Commercial-Off-the-Shelf HPC Systems Based on General-Purpose Computing on Graphics Processing Units (W) • Distributed-Wireless Technology (W) • Cloud Computing Technology (W)	• Optimization of Server Software (L) • Cyber Security (L) • Software Architectures for Security and Assurance in Cloud Environments (L) • Optimization of Supercomputer Use (F) • Cloud Services/Computing (F)	• Cyber Energy-Management System (F) • HPC-Enabled Autonomy (W) • Use of Intelligent Systems to Decrease Labor/ Energy Usage 10%/Year (W)
New	Game Changers		• Emerging Nanotechnology (L) • Emerging Superconducting (F) • Emerging Quantum Devices (F)	• Superconducting on Demand (F) • Ready Availability of Nanotechnology (F) • Ready Availability of Quantum (F)

Empowering the Mission

Air Force missions, such as persistent surveillance of large areas, require massive data analytics on supercomputers to deliver the critical capability of finding the proverbial "needle in the haystack" and thereby help humans avoid sensory overload. At another extreme, covert special operations forces have limited communications, time, and battery capacity yet need portable computation that only a few years ago would have necessitated a supercomputer. Even more daunting, autonomous operation of bird-sized micro air vehicles demands that high-performance computer operations be carried out in micro physical spaces. This issue will become more acute as vehicles shrink to bug size by 2020. The combination of massive data analytics on supercomputers and embedded high-performance computing enables new mission capabilities for the Air Force.

As captured in the first section of table 3, achieving energy efficiency at the system level and finding the technical means for another 700-fold improvement over the next 15 years address all of these mission needs. Technology advances such as three-dimensional stacking can be game changers but not if the stack overheats from power-hungry chips. In addition to improvements from computer architecture, packaging, and system integration, one can gain much by considering the interplay of algorithms and software with the underlying hardware and with the software architecture itself. The 500-teraflop Condor supercomputer at the AFRL (fig. 8) has shown that attaining such balance can deliver order-of-magnitude improvements in energy efficiency.[7] By combining 1,716 Sony Playstation 3s and 176 Nvidia general-purpose graphical processing units, the system can take on a variety of compute-intensive analytic problems and sustain over 50 percent of its peak performance while dissipating only 257 kW. However, case studies have repeatedly shown that mismatches among mission applications, algorithms, and architectures can lead to gross inefficiencies, sometimes causing greater than 100-fold increases in run times.

Figure 8. Condor. (From "Playstations in Racks," DoD Live, accessed 6 February 2012, http://www.dodlive.mil/index.php/2010/12/dodlive-bloggers-roundtable-condor-supercomputer/playstations-in-racks/.)

Finally, the embedded nature of much mission-oriented computing poses additional technical challenges for energy storage and generation from renewable sources. Nanotechnology advances leading to supercapacitors could dramatically extend mission capability and help meet tight size and weight constraints, as captured in the renewables section of table 3.

Optimizing Human/Machine Systems

As articulated in the second section of table 3, to reduce energy demand, the Air Force needs to advance its culture to become more aware of and conservative of its energy in conducting everyday cyber duties. Better measurement and social media (e.g., microblogging, personalized dashboards) can enhance awareness of and guide energy-efficient attitudes, beliefs, and behavior. Improved sensing of human behavior can anticipate the latter and thereby improve performance, guard against insider threats, and elevate trust in autonomy. Research in areas such as intelligence amplification, augmented cognition, and integrated cyber and human systems is essential for effectively managing the data volumes, processing needs, and decision speeds of cyber. Optimizing human/machine systems promises force multiplication, greater efficiencies and resilience, and increased operational tempo.

Enhancing Agility and Resilience

The third section of table 3 addresses the enhancement of cyber agility and resilience through electricity efficiencies and cloud computing (the provision of computation, software, data access, and storage services that are location independent, scalable, and virtual). The Air Force must be able to continually monitor and assess our energy sources and have the agility to move amongst alternatives quickly—perhaps in an unpredictable fashion—implying secure and intelligent monitoring and control of smart power grids. Equally important, we must have agility where and when we choose to carry out missions in cyberspace—by means of cloud computing, for example. Moreover, support infrastructure can be located near low-cost energy sources. However, to ensure that the Air Force can operate in cloud environments with assured confidentiality, integrity, and availability in friendly and hostile environments, we must invest in S&T for automated mission assurance, cyber agility, and resilience.

Inventing New Foundations

The final section of table 3 depicts S&T areas that could "change the game" as regards cyber energy. These include advances in the interrelated technologies of quantum computing, nanotechnology, and superconducting materials.

Infrastructure Energy

Air Force infrastructure energy supports missions in air, space, and cyberspace in both fixed and expeditionary bases, encompassing energy acquisition, storage, and distribution. Currently, 85 renewable-energy projects at 43 bases are in operation, and another 19 are planned for FY 2011–14 (fig. 9), placing the Air Force ahead of its goal of 7.5 percent renewable energy by FY 2013. Many of infrastructure energy's needs call for ambitious but attainable implementations of technologies and best practices used in the commercial sector. Particularly problematic are energy security at the service's main operational bases and support of forward-deployed forces, the latter implying additional logistic burdens and costs associated with providing power to these increasingly capable and, thus, power-hungry forward positions.[8]

Figure 9. Green building. Cool-roof technology and a solar-generated hot water system are expected to help produce energy savings of 9 percent at the new fitness center at Tyndall AFB, Florida. (US Air Force photo, accessed 6 February 2012, http://www.af.mil/shared/media/photodb/photos/100513-F-1234E-102.jpg.)

Table 4 outlines technologies for infrastructure energy that the Air Force should lead, follow, or watch in the near term, midterm, and far term to meet energy-reduction and mission goals outlined in the *Air Force Energy Plan 2010*.

Table 4. Infrastructure energy science and technology

Area	Near (FY 11–15)	Mid (FY 16–20)	Far (FY 21–25)
Energy and Water Efficiency	• Implementation of Smart Grid Technologies Including Advanced Building Energy and Water Management Systems (F) • Development of Integrated Models to Analyze Energy and Water System Interdependence (F) • Investigation of Low-Energy Heating and Cooling Technologies (F)	• Autonomous, Multifuel (Omnivorous) Enabled Smart Grid (F) • Smart Building Technologies (F)	• Integrated Energy System Combining Renewable Energy with Nuclear Energy Sources and Innovative Energy Storage and Water-Conservation Technologies (F)
Renewables	• Expansion of Biomass for Electricity at Appropriate Air Force Installations (L) • Implementation of Petroleum-Replacement Technologies (L) • Focus on Increasing Efficiency of Current Wind and Solar Technologies (F)	• Thermochemical Production of Electricity and Fuel from Solar Energy (L) • Photovoltaic Technologies for Reducing Logistic Fuel Consumption (F) • Plastic to Tactical Fuel-Conversion Technologies Implemented at Forward Operating Bases (F)	• Flexible, On-Site Energy Harvesting/Consumption—Photovoltaic, Solar, Wind, Biomass, etc. (F) • Utilization of Microbial Fuel Cells for Waste-to-Fuel Capability (W) • New Concepts for Direct-Light-to-Electricity Conversion Technologies (W)
Energy Storage	• Incorporation of Adaptable Storage Technologies into the Base Grid; Emerging Battery Technologies (L) • Electrochemical Flow Capacitor—10X Improvement in Storage Capacity (L)	• Exploitation of Metal Hydrides—20X Improvement (L) • Exploitation of Sodium-Air Battery—10X Improvement (F)	• Superconducting Magnetic Energy Storage—Game Changer—to Enable Rapid Charge and Discharge Cycles (W)
Cultural Change	• Development of Energy Assessment and Grid-Monitoring Tools (L)	• Energy Consumption as a Mission-Impact Metric (L)	
	• Energy Efficiency as a Key Performance Parameter (F)	• Rapid Insertion and Exploitation of Emerging Energy Technologies (L)	• Adoption of Nuclear Energy Technologies (W)

Energy and Water Efficiency

The first section of table 4 concerns energy and water efficiency. Broad deployment of scalable management systems for building energy that apply advanced energy diagnostics and alternative, energy-efficient HVAC operation strategies could realize savings of at least 20 percent (more than $200 million) in HVAC energy consumption at DOD facilities.[9] Integrated and dynamic models of electricity, thermal, fuel, water, and waste systems can enable facility managers and, eventually, autonomous controllers to understand building-energy performance; diagnose building-energy faults; and assess alternative, energy-efficient HVAC operation and electrical consumption strategies to increase infrastructure efficiency, robustness, and resiliency.

Renewables

As captured in the second section of table 4, renewables promise sustainable and environmentally friendly energy supply (fig. 10). For example, biofuels can increase the supply of liquid fuels for forward-deployed tactical vehicles and HVACs. Waste-to-energy technologies can reduce energy demands and improve the environment. Although existing technologies such as biomass conversion, wind electricity, or photovoltaic cells can provide stop-gap measures for energy-independent facilities, liquid-fuel production requires the development of new solar-to-fuel technologies such as the Department of Energy–sponsored pilot at Sandia National Laboratories (the Counter-Rotating Ring Receiver Reactor Recuperator). Long-term possibilities include microbial fuel cells—bioreactors that convert energy stored in the chemical bonds of organic compounds directly into electrical energy without contributing additional carbon emissions.

Figure 10. Renewable wind. (US Air Force photo, accessed 6 February 2012, http://www.af.mil/shared/media/photodb/photos/100406-F-2907C-414.jpg.)

Energy Storage

The third section of table 4 summarizes the fact that highly efficient storage systems, which can quickly respond to changes in demand to stabilize voltage and frequency of the electrical grid, are essential to support key base operations. Given their rapid charge/discharge ability, supercapacitors show considerable potential for addressing load-leveling, power-shaving, and grid-stabilization issues. Compared to batteries, supercapacitors provide 10-times-higher power density, 100-times-faster charge/discharge rates, and 1,000-times-longer lifetimes at 30–80 percent lower cost. However, current technologies suffer from low energy density (about 20-times lower), high cost, and self-discharge issues, which limit widespread implementation. In the midterm, the federal government has invested significantly to improve the efficiency of batteries, solid-oxide fuel cells, photovoltaics, high-temperature semiconductors, and phase-change materials. In the long term, new high-temperature superconducting materials would become key enablers of magnetic-energy storage systems, yielding a smaller time delay between charge and discharge and providing almost instantaneously available power, very high output for short periods of time, and high-energy density.

Cultural Change

As captured in the fourth section of table 4, institutionalizing change will involve not only material advances but also human ones. Grid monitoring and assessment can enhance individual and collective energy awareness, which, in turn, motivates behavior change. Social media can be employed to drive community behavior. Developers, acquirers, testers, and operators must incorporate energy as a key parameter of infrastructure performance, explicitly connecting energy to mission effects and driving toward an assured energy advantage that is robust and resilient. The National Defense Authorization Act of 2010 directs the DOD to determine the feasibility of nuclear power plants on its installations. For example, autosafing, buried, and waste-reusing small modular nuclear reactors could offer enhanced grid security to Air Force bases with requirements of less than 300 megawatts. Finally, the service should accelerate the assessment and transition of energy solutions to operations by using energy-infrastructure test beds such as experimental RPAs or select pilot bases.

Cross Cutting, Enabling Science and Technology

Illustrated in figure 11, new ideas emerging from research in basic science have the potential to fundamentally transform the energy landscape across all of the domains discussed above. For example, in terms of energy generation, these advances will enable ultraefficient photovoltaics, biofuels, and sun to petrol, as well as small modular reactors that are passively safe and use waste fuel. For enhanced energy storage, S&T developments will lead to advanced batteries with high power, density, and variable charge/discharge cycles; ultracapacitors;

Figure 11. Cross cutting, enabling science and technology

high-power flywheels; and superconducting magnetic energy. Nanomaterials will make possible lightweight, high-strength structures as well as nanoelectronics. Furthermore, cloud and green supercomputing will enable resilient and efficient computation, and energy micromonitoring and control will enhance energy situational awareness and motivate energy-saving behavior.

Finally, in the longer term, several scientific areas that cut across multiple domains identified in the Air Force's *Report on Technology Horizons* have the potential to transform the energy landscape for the service across missions in air, space, cyberspace, and infrastructure.[10] These include collective behavior in nanostructured materials; lightweight, multifunctional structures; materials and systems under extreme conditions; bioengineering and biomimicry; control in complex systems; information and cyber infrastructure; and trust and autonomy.

The Way Forward

Science and technology can offer advances that translate into operational advantages, including cost savings, energy resiliency, system robustness, and operational readiness. Achieving an "assured energy advantage" across primary missions requires the Air Force to do the following:

- Partner with relevant federal government entities to leverage energy investments. This includes, but is not limited to, the Office of the Secretary of Defense (OSD), Navy, National Aeronautics and Space Administration (NASA), and Federal Aviation Administration in air energy; NASA and the National Reconnaissance Office in space energy; US Cyber Command and the National Security Agency in cyber energy; and the OSD, Department of Energy's Applied Research Program Activity–Energy, Department of Homeland Security, and National Science Foundation in infrastructure energy.
- Focus precious Air Force resources on the service's unique mission requirements in air, space, cyberspace, and infrastructure en-

ergy, emphasizing both financial and operational benefits as well as outcomes at a system-of-systems level.

- Deliberately choose roles that focus investments—for example, acting as an energy leader in research and development of air and space energy, a fast follower / early adopter of others' cyber energy advancements, and a watcher in infrastructure energy, except in unique Air Force niches (e.g., rapid and secure grid deployment and expeditionary energy).
- Make the efficiency of air operations a first priority and ground operations (e.g., space-operations control, data-processing centers, and infrastructure-process energy) a second priority.
- Employ a systems approach that subjects solutions to a business-case analysis prior to adoption and that considers interdependencies across the domains of air, space, cyberspace, and infrastructure, employing evaluation metrics to guide investments that comprehensively consider fully burdened costs and life-cycle costs.
- Accelerate assessment and transition through the employment of test beds such as experimental RPAs, or select bases that can pilot operations as well as process energy solutions.
- Create relevant energy education and training and develop a culture of energy understanding that motivates the desired behavior of communities to assure an energy advantage.

Because of its pervasive nature, energy is a shared responsibility, and the realization of the *Energy Horizons* vision will demand a full team effort to realize the "assured energy advantage" in the joint and coalition fight. Key stakeholder communities and required actions include the following:

- *Energy Awareness*. Increase energy awareness to guide energy-efficient behaviors through enhanced energy communication, training, situational awareness, and incentives/recognition.

- *Science and Technology*. Aggressively pursue the most promising energy S&T vectors as articulated in *Energy Horizons*, focusing on cross-cutting enablers that promise to maximize return on investment, future savings, and operational capability/advantage such as high-efficiency propulsion and photovoltaics, revolutionary materials, and high-capacity storage.
- *Test and Evaluation*. Assess and guide systems from design to operations to meet the Air Force's energy goals.
- *Analysis and Planning*. Ensure rigorous energy analysis and the supporting force mix to attain the Air Force's focused objectives. Additionally, develop an accepted methodology to calculate, monetize, or otherwise quantify the value of "energy security," considering multiple variables such as cost, environmental footprint, physical security, resilience, flexibility/adaptation, and geopolitical risk.
- *Requirement and Acquisition*. Consistent with the DOD's operational energy strategy, which articulates energy as a key performance parameter, provide an assured energy advantage in requirements and acquisitions that is resilient and evolutionary.
- *Operations*. Advance operational concepts, tactics, techniques, and procedures that simultaneously enhance efficiency, resiliency, and operational effectiveness.
- *Education and Training*. Ensure that sufficient expertise in science, technology, engineering, and mathematics exists in multiple energy sciences across the integrated force to sustain the human capital necessary to realize our energy advantage.

In summary, the vision of the *Energy Horizons* report promises an "assured energy advantage across air, space, cyberspace and infrastructure," mentioned above. *Energy Horizons* is essential to achieving the Air Force's economic, environmental, and operational imperatives while at the same time supporting national objectives of economic development, environmental stewardship, and supply independence. By carefully focusing on the near term, midterm, and far term as a deliberate leader, fast follower, or watcher, and by working in full partnership with other services and agencies, the Air Force can more rapidly and efficiently advance its *Energy Horizons*. Thus, *Energy Horizons* helps our service ensure not only energy robustness, resiliency, and readiness but also concomitant efficiency in peacetime operations, independence of action during humanitarian and disaster relief, and military superiority during conflict. ✪

Notes

1. US Air Force Chief Scientist, *Energy Horizons: A Science and Technology Vision for Air Force Energy, 2011–2026*, Report no. AF/ST-TR-11-01-PR (Washington, DC: United States Air Force Chief Scientist [AF/ST], 15 December 2011), http://www.af.mil/information/energyhorizons.asp; Department of Defense, *Energy for the Warfighter: Operational Energy Strategy* (Washington, DC: Department of Defense, 2011), http://energy.defense.gov/OES_report_to_congress.pdf; Headquarters US Air Force, *Air Force Energy Plan 2010* (Washington, DC: Headquarters US Air Force, 2010), http://www.dm.af.mil/shared/media/document/AFD-101202-066.pdf; and National Science and Technology Council, *National Aeronautics Research and Development Plan* (Washington, DC: National Science and Technology Council, February 2010), http://www.whitehouse.gov/sites/default/files/microsites/ostp/aero-rdplan-2010.pdf.
2. Headquarters US Air Force, *Air Force Energy Plan 2010*, 5.
3. US Air Force Chief Scientist, *Energy Horizons*, 2.
4. James Mattice et al., *Technology Insertion for Energy Savings in the Legacy Fleet*, Report no. AFRL-RZ-WP-TR-2011-2092 (Wright-Patterson AFB, OH: Air Force Research Laboratory, July 2011), 132, 284.
5. Ann Karagozian et al., *Technology Options for Improved Air Vehicle Fuel Efficiency*, Report no. SAB-TR-06-04 (Washington, DC: Air Force Scientific Advisory Board, May 2006), 16, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA456127.
6. Jonathan Koomey, *Growth in Data Center Electricity Use, 2005 to 2010* (Oakland, CA: Analytics Press, 2011), 6.
7. SSgt J. Paul Croxon, "What's under the Hood? Air Force Scientists Build Supercomputer Using Game Consoles," *Airman Magazine* 54, no. 7 (November–December 2010): 17–19, http://www.af.mil/shared/media/document/AFD-110601-016.pdf.
8. See Air Force Scientific Advisory Board, *Alternative Sources of Energy for U.S. Air Force Bases* (Washington, DC: Air Force Scientific Advisory Board, December 2009).
9. Executive Order (EO) 13423, "Strengthening Federal Environmental, Energy, and Transportation Management," 24 January 2007; and EO 13514, "Federal Leadership in Environmental, Energy, and Economic Performance," 5 October 2009. Both of these EOs implement the Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding, including the Energy Policy Act of 2005.

10. *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: United States Air Force Chief Scientist [AF/ST], 15 May 2010), http://www.af.mil/shared/media/document/AFD-101130-062.pdf.

Dr. Mark T. Maybury

Dr. Maybury (BA, College of the Holy Cross; MBA, Rensselaer Polytechnic Institute; MPhil, PhD, Cambridge University) is chief scientist of the US Air Force, serving as chief scientific adviser to the chief of staff and secretary of the Air Force and providing assessments on a wide range of scientific and technical issues affecting the Air Force mission. In this role, he identifies and analyzes technical issues, bringing them to the attention of Air Force leaders, and interacts with other Air Staff principals, operational commanders, and combatant commands as well as acquisition and science and technology (S&T) communities to address cross-organizational technical issues and solutions. Dr. Maybury also interacts with other services and the Office of the Secretary of Defense on issues affecting the Air Force's in-house technical enterprise. Serving on the Steering Committee and Senior Review Group of the Air Force Scientific Advisory Board (SAB), he is the principal S&T representative of the Air Force to the civilian scientific and engineering community and to the public at large. Dr. Maybury served on the SAB as vice-chair of S&T, vice-chair of a study on remotely piloted aircraft, and a member of studies on commercial space, rapid on-orbit checkout, and operating in contested cyberspace. He also chaired an SAB information S&T review and vice-chaired a human-effectiveness S&T review at the Air Force Research Laboratory. Additionally he has served on studies for the Defense Science Board and the Intelligence Science Board. A former Air Force officer and Fellow of the Institute of Electrical and Electronics Engineers, Dr. Maybury is currently on a leave of absence as an executive director at the MITRE Corporation. He has edited or coauthored 10 books, authored over 60 refereed publications, and received several US patents.