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SUBJECT: Fiscal Year 2017 Air Force Research Laboratory

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INTRODUCTION

Mr. Chairman, Members of the Subcommittee and Staff, I am pleased to have the opportunity to provide testimony on the Air Force Research Laboratory, our Service's premiere research organization and our efforts to lead the discovery, development, and integration of affordable warfighting technologies in the face of a dynamic, complex and unpredictable future.

Headquartered at Wright-Patterson Air Force Base (AFB), Ohio, the Air Force Research Laboratory (AFRL) leads a worldwide government, industry, and academia partnership in the discovery, development, and integration of affordable warfighting technologies for the Air Force. AFRL is the single Air Force laboratory and the largest single defense laboratory world-wide. It is responsible for planning and executing the Air Force Science and Technology (S&T) program with world-class facilities across the nation. The laboratory provides leading-edge warfighting capabilities and revolutionary technologies that keep our air, space, and cyberspace forces the world's best.

The Air Force, through AFRL, manages Air Force S&T as an integrated program by using AFRL's special resources to invest in future capabilities and provide the warfighter with near-term technical support. AFRL carefully balances the investment portfolio in basic research, applied research, and advanced technology development, allocated between in-house and contracted activities, to produce both evolutionary and revolutionary technologies focused on 12 Air Force Service Core Functions and capabilities. This statement describes how AFRL executes the Air Force S&T Strategy.

As stated in the *Air Force Posture Statement 2016*, "today's national security challenges come from a combination of strong states that are challenging world order, weak states that cannot preserve order, and poorly governed spaces that provide sanctuary to extremists who seek to destabilize the globe." This shift in the geopolitical landscape, along with the rapid globalization of technology, is allowing adversaries to boldly challenge America's superiority in air, space, and cyberspace. AFRL is uniquely positioned, as one of the few organizations responsible for research and development supporting all three domains, to ensure that we have the capabilities we need to dominate the current fight, prepare for the future fight, and perhaps deter that future fight from happening.

In line with the *2016 Air Force Materiel Command Strategic Plan* and the *Air Force Future Operating Concept,* AFRL is pursuing additional agility and innovation into our capability development processes, workforce and infrastructure. AFRL's investments in strategic agility support the building blocks of the Department's Third Offset Strategy, the Fiscal Year 2017 Air Force S&T Program and the Long Range Research and Development Planning Program initiatives.

From an acquisition perspective, AFRL investments also address and support the Better Buying Power (BBP) 3.0 initiatives under the leadership of Mr. Frank Kendall, Under Secretary of Defense for Acquisition, Technology and Logistics (AT&L). The BBP 3.0 initiatives are endeavoring to strengthen our ability to innovate, achieve technical excellence, and field dominant military capabilities.

The following testimony provides an overview of the Air Force Research Laboratory as an organization. It addresses our pursuit of strategic agility, the impact of our warfighter-focused S&T programs (game-changing, enabling, relevant, and rapid technologies), the stand-up of a strategic development planning and experimentation office, the importance of prototyping in our mission, and leveraging the critical contributions of our world-class workforce and infrastructure.

AIR FORCE RESEARCH LABORATORY STRUCTURE

AFRL is a single full-spectrum research organization that executes the Air Force's investment portfolio in basic research, applied research and advanced technology development. AFRL is unique among the Services because the laboratory directs *all* Air Force efforts to discover, develop and integrate affordable aerospace warfighting technologies. Two decades ago, the Air Force laboratory system spread research across 14 different organizations nationwide. In 1990, these locations were merged into four "superlabs." Finally, in 1997, those were merged into a single, unified structure to create AFRL and bring Air Force S&T to a new level of efficiency, collaboration and innovation.

AFRL Commander

Aside from serving as the AFRL Commander, I am also the Air Force Technology Executive Officer (TEO). In this capacity, I meet with the Secretary of the Air Force and Chief of Staff of the Air Force every six months in order to maintain alignment with Air Force needs and priorities, and to review progress. These meetings occur at S&T Forums where the health of AFRL and the Air Force S&T Enterprise is discussed. We engage with each Air Force customer (Major Commands, Program Executive Officers and Program Managers) at least twice a year during formal Applied Technology Councils as well as with a TEO Review every 18 months.

Directorates

AFRL Headquarters staff provides the workforce and infrastructure necessary to ensure that AFRL can accomplish its mission and assist me in formulating and disseminating policies, plans, and directives affecting the lab. Aside from AFRL Headquarter functions, there are nine Technology Directorates (TD)- Air Force Office of Scientific Research, Aerospace Systems, Directed Energy, Information, Airman Systems, Munitions, Sensors, Space Vehicles and Materials and Manufacturing. The 711th Human Performance Wing is a large operational unit within AFRL and includes Human Systems and Integration, Air Force School of Aerospace Medicine and the Airman Systems TD. Each of our TD directors also serves as a Capability Lead responsible for meeting the needs of Air Force Service Core Functions.

Research Sites

AFRL maintains 12 operating locations across the globe. AFRL Headquarters, the 711th Human Performance Wing and four TDs (Aerospace Systems, Sensors, Airman Systems and Materials and Manufacturing) are located at Wright-Patterson AFB, Ohio. The Air Force Office of Scientific Research is located in Arlington, Virginia. Our Munitions Directorate is at Eglin AFB, Florida. Our Information Directorate is in Rome, New York and the Directed Energy and Space Vehicles directorates are located at the Phillips Research Site, Kirtland AFB, New Mexico. Additionally, we maintain facilities in Maui,

Hawaii; Edwards AFB, California; Fort Sam Houston, Texas; Arnold AFB, Tennessee; Santiago, Chile; London, United Kingdom; and Tokyo, Japan.

AIR FORCE RESEARCH LABORATORY FISCAL YEAR 2017 S&T PROGRAM AND ASSOCIATED EFFORTS

We are excited that Air Force senior leaders and Congress are committed to S&T and are embracing efforts in capability development. The Air Force Fiscal Year 2017 President's Budget request for S&T is approximately $2.5 billion. This is an increase of $108 million or a 4.5% increase from the Fiscal Year 2016 President's Budget request. We have emphasized research in hypersonic and low cost cruise missile technologies, advanced air combat missiles, and position, navigation and timing (PNT) technologies to highlight capabilities focused on operations in anti-access and area-denial (A2AD) environments. These technologies, discussed later, directly increase support of the Defense Department's Long Range Research and Development Planning Program and Third Offset Strategy.

The Air Force Fiscal Year 2017 President's Budget request also includes funding in Budget Activity 4 (Advanced Component Development and Prototypes) and in Budget Activity 6 (RDT&E Management Support) part of which supports AFRL prototyping, experimentation, and modeling and simulation efforts. More information on these efforts is provided later in this statement.

AGILITY IN CAPABILITY DEVELOPMENT

To capitalize on the increasingly dynamic environment, AFRL is aggressively pursuing a path toward *strategic agility* by providing technologies to keep the fight unfair (revolutionary), focused on near and midterm needs (relevant) and delivering the warfighter's needs "right now" (responsive). Additionally, AFRL is focused on achieving greater agility in how we organize, train, equip, and employ our laboratory to provide a *strategic* advantage over potential adversaries.

This is not an entirely new endeavor. In addition to the *S&T Guiding Principles*, the Secretary of the Air Force laid out seven specific S&T goals focusing available resources on issues of critical importance to the Air Force. These goals are to leverage and create technology trade space to support near-, mid-, and far-term acquisition programs, innovate technical solutions to rapidly respond to urgent warfighter needs, develop concepts and create new S&T options addressing threats and maintain/increase capability, invent concepts and S&T supporting *Global Vigilance, Global Reach, Global Power*, employ business practices increasing inventiveness, productivity and responsiveness, acquire, develop and retain a high-performing workforce, and invest in core S&T infrastructure to ensure future health.

AFRL responds in real time to Air Force current and future demand signals through the use of Capability Collaboration Teams (CCTs). CCTs interact directly with Air Force Major Commands (MAJCOMS), Centers, and Program Element Officers (PEOs) to align Air Force S&T with Air Force priorities and improve the return on investment provided by AFRL.

AFRL is integral to the reinvigoration of development planning at the Air Force enterprise level to formulate truly innovative strategic choices and leverage the attributes of agility in our capability development. Development planning enables us to understand and synthesize future warfighting needs and reconcile those with available and potential capabilities. It serves as a key process to support Air Force strategic decisions. To provide this capability AFRL will engage in: systems engineering to formulate and evaluate viable concepts; operational trade space analysis and definition; technology shortfall identification; S&T needs and gap analysis; and requirements refinement.

In conjunction with development planning, AFRL is conducting experimentation and prototyping activities exploring the full range of multi-domain innovative materiel and non-materiel solution options. These activities provide an environment where our Airmen can take smart risks while testing innovative ideas.

Through the newly formed Strategic Development Planning and Experimentation Office, AFRL is supporting the Enterprise Capability Collaboration Team (ECCT) approach to facilitate development planning for our highest-priority mission areas. ECCTs have the freedom to explore concepts with a direct path to senior leadership for quicker decisions on courses of action to increase agility across the enterprise.

CONTRIBUTION OF AIR FORCE S&T IN AGILE CAPABILITY DEVELOPMENT

Our S&T program lays the technological foundation for the current and future Air Force to assure America's security through *Global Vigilance, Global Reach, and Global Power*. The Air Force emphasized the role of S&T by dedicating an annex in the *Strategic Master Plan*. We adhere closely to the strategic approach to S&T outlined in the annex and provide the supporting elements necessary to bring forth the next generation of capabilities.

Game-Changing (Revolutionary) Technologies

As outlined in *America's Air Force: A Call to the Future*, AFRL is focused on several game-changing technologies to amplify and augment the enduring attributes of airpower—speed, range, flexibility and precision. These five game-changing technologies are autonomous systems, unmanned systems, hypersonics, directed energy and nanotechnology. Our efforts in autonomous systems and unmanned systems in particular provide key support to the realization of the five enablers of the Department's Third Offset Strategy.

Autonomous Systems

Autonomy has the potential to enhance Air Force readiness for increasingly complex, future operating environments. We are seeking to enable the *right balance* of human and machine capability to meet Air Force challenges in the future. Our focus is on growing autonomous system capability, integrated with the human capacity to perform in a high-tempo, complex decision environment and to optimize airmen working together with machines both effectively and efficiently.

AFRL's goal for autonomous systems is to increase efficiency; empowering airmen to engage in a more rigorous analysis that leverages available data across multiple domains and mission areas. This vision aligns with the Third Offset Strategy underscoring optimization of human decision making with technology.

Current autonomy efforts are focused on enabling improved safety, efficiency of operations, multi-system collaboration, and command and control. We are building from the previous ground collision avoidance systems to demonstrate air collision avoidance. We will then move on to autonomous formation flight. We are also transitioning technologies to aid the Intelligence, Surveillance and Reconnaissance (ISR) analyst in efficiently producing intelligence information. In Unmanned Aerial Vehicle (UAV) ISR, technologies are in development to demonstrate the benefit of multi-system collaboration. This will ensure target identification and tracking without the need for airman control. For command and control, autonomy technologies are being demonstrated to support decision-making through course of action generation and execution monitoring.

AFRL completed demonstrations of early autonomy capabilities as well as initial multi- UAV autonomy. We are currently demonstrating user interface technologies that are naturalistic and enhance human trust and teaming across the Department to mature autonomy technologies. Efforts with both the Army and Navy are demonstrating multiple platform collaboration technologies across the ground, marine and air environments.

Our work is postured to advance autonomy technologies for future applications. We are on point to demonstrate an intelligent analytic system that will exploit existing data and integrate it with incoming sensor data to provide more complete intelligence for the airman. Additionally, AFRL will demonstrate the technologies needed for a UAV to autonomously balance the use of resources with unplanned events through a dynamic, contested environment. We will enable autonomous systems to receive mission objectives and be able to coordinate mission execution with other unmanned systems to optimize operations and extend the capabilities of the manned flight lead.

Unmanned Systems

AFRL is pressing forward on the full integration and exploitation of unmanned air systems (UAS) for an agile combat force. The advent of UAS introduced a class of air platforms that not only may be smaller and cheaper, but also provide new freedom to distribute operational risk-taking. AFRL is creating the technology base to pair manned and unmanned platforms together and also to build systems with a large number of unmanned platforms. With UAS, we are forging a path for rapid development and frequent technology refresh to fuel future warfighting agility.

AFRL is working closely with Air Force Special Operations Command to integrate tube-launched UAS; providing additional sensing in weather and at stand-off. AFRL has also developed a technology base allowing for the teaming of UAS with our future fighter fleet, augmenting the front-edge fight with additional weapon and sensing resources.

We see additional opportunity in fielding teams of smaller UAS that are individually limited but collectively effective. AFRL has laid a foundation for autonomous and cooperative flight, from fundamental theory, to computer models and multiple flight demonstrations. We are also developing operationally relevant sensor options in very small form factors. The technology breadth of AFRL also allows us to converge expertise in both aircraft and munition technology to develop this new class of high performing small UAS.

One aspect of our mission is reworking the Air Force design and manufacturing processes. The Laboratory is actively developing an approach to designing attritable aircraft with a limited service life that can be produced at a fraction of the cost of other platforms. This capability relies on AFRL's additive and flexible manufacturing efforts, combining AFRL's world class in-house resources with a network of national manufacturing partners.

The rapid onset of attritable and expendable UAS aircraft is enabling AFRL to revolutionize ISR with new, highly agile, distributed capability platforms. We are developing low cost UAS platforms to obtain

persistent situational awareness within contested environments. Our experts enabled persistent situational awareness by decoupling high-performance hardware from long-lifetime platforms in new sensor designs. We are also working on autonomy in UAS flight control, allocation of sensor assets and fusion of sensor data to provide much faster access to critical ISR information with greatly reduced UAS flight crew requirements.

We are leveraging aspects of UAS, such as open system architectures, to reduce lifecycle costs as ISR and UAS technologies evolve at different paces. This will greatly increase a commander's options to rapidly deploy ISR flight packages tailored to specific missions. These key shifts in sensor research and development, now under way within AFRL, will provide persistent situational awareness on the battlefield within increasingly challenging operational environments.

Hypersonics

Hypersonics are one of the game-changers providing high-speed options for engaging time sensitive targets, while improving the survivability of Air Force systems. This is a discipline where several technologies must integrate together to deliver capability options for the warfighter. AFRL facilitates hypersonic technology development coordination and collaboration by utilizing its lead position in the Air Platforms Community of Interest (CoI), High Speed/Hypersonics Sub-area. This CoI draws representatives from DoD agencies (Air Force, Navy, Army, DARPA) and NASA to mature required technologies.

We also conduct our own technology development across the full S&T spectrum from basic to applied research and through advanced technology development; an effort that involves the majority of our technical directorates.

Examples of the diverse set of hypersonic technology development programs within AFRL include:

High Speed Strike Weapon (HSSW) Technology Maturation (Tech Mat): This program develops technologies for a high speed strike weapon enabling responsive and long-range strike capabilities. It focuses on longer term enabling/enhancing technologies.

Medium Scale Critical Components (MSCC): This is the exploration of performance and reusability of larger scramjet engines with a mass capture of approximately ten times (10X) that of the X-51A engine.

MSCC is a great example of collaborative effort with Arnold Engineering Development Complex's Aerodynamic and Propulsion Test Unit (APTU) facility.

Hypersonic International Flight Research (HIFiRE): This program investigates fundamental hypersonic phenomena, advances component technologies and instrumentation, and conducts flight experiments in relevant environments in collaboration with Australia. HIFiRE has produced vast quantities of hypersonic data, validated numerous component technologies and demonstrated an affordable flight test approach.

Underpinning all of the AFRL investments in hypersonic systems is sustained, robust basic and applied research. We are currently exploring Hot Structure Behavior Prediction, Fluid Structure Interaction, Non-equilibrium Flows, Sensors for Engine Control, Ignition and Flame Propagation and Boundary Layer Transition.

Directed Energy

The Directed Energy (DE) technologies AFRL is developing have the potential to provide unprecedented self-defense, air superiority, and precision strike capabilities with speed of light engagement, minimal collateral damage and a deep magazine. In the next five to ten years, it may be possible to use matured DE technologies to enhance the survivability of legacy and future aircraft and defend forward bases against aircraft and missiles.

The Secretary of the Air Force chartered a multi-organizational, inter-disciplinary, Integrated Product Team (IPT) to develop an Air Force DE Weapon Flight Plan. The Flight Plan will guide comprehensive activities across the Air Force to support operational DE and enable delivery of key effects to the battlefield.

Through the Strategic Development Planning and Experimentation Office, AFRL is leading completion of the Flight Plan and will identify and mature all primary and support system/sub-system technologies that are required to employ game-changing DE weapons. To support this, we have already developed collaborative multi-service/agency technology development roadmaps to inform the DE Weapon Flight Plan.

AFRL is currently engaging in military utility analysis and experimentation to realize the highest payoff DE weapons for near-term transition and long-term continued investment. With recent world-wide proliferation of UAV and regional missile threats to our bases, our analysis suggests that ground based DE systems for force protection could be transitioned in the near-term. AFRL is also addressing potential

operational deficiencies of DE systems through field experiments like the Demonstrator Laser Weapon System (DLWS) at White Sands Missile Range.

Since the 1980's, airborne High Energy Laser (HEL) systems have demonstrated the ability to precisely engage difficult targets from the air. These were primarily gas or chemical lasers that were large, heavy, and logistically difficult to support. In the last 15 years, DoD, the Air Force, and commercial investment has driven significant advances in electric (solid state) laser and high power radio frequency (HPRF) technologies and systems.

AFRL is continuing to capitalize on HPRF technology advances by pursuing a joint airborne counter electronics demonstration called High Power Joint Electromagnetic Non-Kinetic Strike (HiJENKS) in partnership with the Navy.

We are also currently engaged in the Self-Protect High-Energy Laser Demonstrator (SHiELD). This program includes two incremental phases. In the first phase, we will track agile targets at range to show that we can mitigate complex aerodynamic disturbances. The second phase will incorporate a moderate powered laser to assess performance in an operationally relevant environment.

Nanotechnology

Nanoscale structures create unique properties by leveraging both unique surface physics and the exploitation of quantum effects. AFRL is currently infusing international and commercial investment at the component level to enable improvements in a variety of Air Force capabilities including ISR, weapons, airframes, and propulsion. We believe the continued development of nanotechnology will produce Air Force game-changing capabilities. Nanotechnology will, in part, underpin technology innovations that will revolutionize future air, space, and cyberspace capabilities by delivering materials, coatings, devices and sensors with new and novel performance.

The past decade of nanotechnology work has been categorized by the investigation of nanomaterials and concepts and through examining the state of the possible. We are leveraging the Manufacturing Institutes across the country and will continue to utilize these and core efforts to drive research and development programs.

Currently, we are developing ultra-small, customized munitions enabled by the precise control of components at the nanoscale. New designs of energetic material, casing and solid propellant are projected to enable higher energy and smaller weapons reducing size and weight while delivering the same or greater effect. We are also learning how to "place" atoms in specific planes at the atomic scale which greatly increases signal to noise and thus efficiency of a sensor. This enables tremendous improvements

with regard to the size, weight, and power consumptions and eliminates the need for large external cooling components.

Multifunctional and adaptive structural materials harden electronics from electromagnetic threats and maintain structural performance during hypersonic conditions. We are developing smart coatings that will provide protections from adverse environments while self-reporting integrity to facilitate sustainability in military systems. Lightweight and pliable electronic systems, such as antennas, energy harvesting, batteries and power conditioning systems are being developed to extend mission duration and capability.

Enabling Technologies

In addition to these game-changing technologies, the Air Force S&T Program also invests in several enabling technologies to facilitate major advances and ensure maximum effectiveness in the near-, mid-, and far term.

Basic Research

AFRL's basic research efforts include working with world class universities, innovative small businesses and government research laboratories to invest in foundational science to generate the new knowledge necessary for the Air Force of tomorrow.

We execute the strategy outlined in *America's Air Force: A Call to the Future* by investing to create and support an innovation network. AFRL is focused on empowering the Air Force to rapidly adjust to both the evolving threat environment and the opportunities afforded by new science and technology. Our basic research program tracks and invests in the best S&T in the world by working with our partners in the Army, Navy, DARPA, and the Defense Threat Reduction Agency. We also monitor and leverage the investments and breakthroughs of the National Science Foundation, NASA, the Department of Energy, the National Institute of Standards and Technology, and intelligence community agencies such as Intelligence Advanced Research Projects Agency (IARPA). We also leverage the basic research investments of our international partners, such as Europe's billion Euro investment in quantum computing research.

The National Science Foundation noted that between 2001 and 2011, the U.S. saw its market share of global research and development attrite from 37 percent to 30 percent. By investing in the best open,

publishable research in the world, we are developing the relationships and collaborations to mitigate—and even turn around—the impact of this trend.

Our basic research program also plays a role in the development of future scientists and engineers. We are combining fundamental research efforts at universities and National Labs with state-of-the-art Air Force facilities and capabilities. The best and brightest students are working directly within the Air Force laboratory infrastructure right from the beginning of their careers.

Live, Virtual, and Constructive (LVC)

The Secure Live, Virtual, and Constructive Advanced Training Environment (SLATE) is an Advanced Technology Demonstration formally commissioned in February 2015 as a result of the 2014 Air Combat Command Acquisition and Sustainment Review to enhance Live Operational Training for the Combat Air Force, specifically the F-35.

The AFRL role is comprised of two main efforts: hardware/software integration and waveform maturation. Under the first effort, a team of industry partners will provide core LVC-enabling technologies for 4th and 5th generation tactical aircraft. The second effort updates the Range Instrumentation Waveform specification to meet the requirements of a 5th generation LVC training environment.

Position, Navigation, and Timing

Positioning, Navigation and Timing (PNT) is a critical enabling technology that supports nearly every Air Force warfighter and weapon system. The Global Positioning System (GPS) is the “go-to” PNT capability; however, we know we need to find alternatives. These alternative PNT technologies must be tailored to the mission, environment and platform in order to be effective. AFRL’s PNT vision is to lead the discovery and development of robust, resilient PNT services that are available anywhere, anytime. Our challenge is to achieve this vision affordably.

The success of the GPS, the world’s first global utility and the gold standard for satellite navigation, cannot be understated. Neither the depth of our GPS dependence, nor the scope of threats, could be envisioned when satellite navigation was first conceived.

AFRL’s Space Vehicles Directorate is planning a revolutionary technology development program to “reinvent” satellite navigation. The Navigation Satellite Technology 3 (NTS-3) is the first program of its kind since the introduction of atomic clocks to spaceflight in the 1970’s. NTS-3’s associated Advanced GPS Technologies (AGT) program plans to launch a truly revolutionary navigation satellite by 2022 that

will be the basis of a yearlong space flight experiment investigating advanced signals, new waveform generation capabilities, improved spacecraft components and an innovative ground control system. NTS-3 and AGT are exploiting agile technologies, such as an on-orbit digitally reprogrammable waveform generator, to ensure our space based capabilities stay a step ahead of our adversaries.

AFRL's Sensors Directorate is working on the business end of the NTS-3 program; namely, how do we build flexible, adaptable, upgradable receivers that can be integrated into Air Force weapons systems? Specifically, we are conducting research into the development of secure, software defined radio-based (SDR) satellite navigation receivers. In FY16, AFRL sponsored the development of the first avionics form factor GPS and Multi-Global Navigation Satellite System (GNSS) compatible SDR. In FY17, we plan to investigate how to appropriately protect military GPS technology in an SDR.

On another front, the Munitions Directorate is collaborating with industry on a relevant Application Specific Integrated Circuit (ASIC) design that combines state-of-the-art anti-jamming capability with a fully modernized military GPS receiver. We will be developing multiple configuration options to suit nearly any munition or aircraft application.

AFRL has partnered with DARPA in the development of the All-Source Positioning and Navigation (ASPN) effort. This effort seeks new algorithms and architectures to rapidly reconfigure a navigation system with new and non-traditional navigation sensors. We have worked with multiple teams from industry and academia to develop reconfigurable, agile navigation system and tested these on the ground, in the air, and at sea.

Our Information Directorate has developed an open, extensible hardware and software architecture that allows AFRL engineers to insert new PNT technology into aircraft with little to no aircraft Operational Flight Program (OFP) modifications. This technology can be used to constrain the navigation solution of an aircraft when GPS is denied. Initial in-flight experiments with vision aided navigation using a targeting pod is planned for FY17.

Finally, AFRL has partnered with the Air Force Life Cycle Management Center, PEO Agile Combat Support and the Joint Systems Sustainment Management Office to develop and encourage the adoption of open architectures for our navigation and timing systems. Our goals are to rapidly and iteratively prototype open system processes, and open standard PNT technology and deliver robust evidence that this "open" approach can improve PNT capability-per-cost and decrease cost-per-PNT-capability across the Air Force enterprise.

Manufacturing Technologies

The Air Force's Manufacturing Technology program is focused on leading paradigm shifts in tomorrow's manufacturing domain. The long-term goal is to change the current, slow platform-specific assembly infrastructure to an agile manufacturing capability.

AFRL is working on innovative approaches to overcome defense-unique production challenges. We supported the F-35 production by enabling reduced production cost, the use of lighter weight components and increases in the durability of components. This, in turn, has improved production yields and performance of turbine blades, automated drilling, and other manufacturing aspects.

We are also developing and implementing advanced manufacturing techniques for open architecture multi-sensor ISR pods and exploring "on-demand" system manufacturing approaches for a low cost attritable aircraft. In additive manufacturing, we are in the midst of establishing the proper set of control experiments and processing methodologies to enable rapid and reliable verification and validation methodologies for parts and components.

The Air Force's ManTech Program continues to provide leadership and subject matter expertise for several of the Administration's National Network for Manufacturing Innovation (NNMI) Institutes. The Air Force is a key leader in the development and implementation of many of these institutes, focused on additive manufacturing, robotics in manufacturing, digital and design innovations, flexible electronics, photonics, and others.

Material Technologies (Sustainment)

AFRL's efforts in sustaining the force remain a priority. We are leading Department efforts to become more innovative and less risk averse in discovering and demonstrating additional methods to sustain our existing assets.

Our commitment in this area provides Non-Destructive Inspection (NDI) techniques and improves maintenance and repair diagnostics, technology for Digital NDI lifecycle data capture and methods for non-destructive quantifying of damaged systems, and characterizes micro-scale material features and analysis tools for life prediction and extension. We are delivering advanced NDI methods and tools, robotic tools for remote access, surgical tools for high velocity maintenance inspections, advanced inspection methods for turbine engines, multi-layered structure evaluation without disassembly and foundational technology for the Air Force's Condition Based Management concept.

To date, we estimate we have provided approximately $2 billion in life cycle cost savings with new low observable inspection technologies and $5 million in annual savings on the inspection of turbine blades. In addition, our efforts have extended structural inspection intervals by utilizing conformal eddy-current probes that improve sensitivity with no negative safety impacts.

Relevant Technologies

Cyber

AFRL cyberspace operations magnify military effects by increasing the efficiency and effectiveness of air and space operations across all domains. At the same time, cyberspace is becoming increasingly contested and denied with risks from malicious insiders, insecure supply chains, and increasingly sophisticated adversaries. AFRL's cyber efforts include:

Cyber-Based Mission Assurance on Trust-enhanced Hardware (CMATH). This is an ATD program for Air Combat Command to address mission assurance and provide cost reduction. CMATH develops secure server virtualization for a weapons system with built-in security features to limit the effectiveness of cyber-attacks and maintain operations in a contested cyber environment.

Autonomous Defensive Cyber Operations (ADCO). AFRL is researching technologies to create force multipliers for defensive cyber operations through machine learning and artificial intelligence. This effort seeks to identify and understand the level of confidence operators have in the employment of autonomous defensive systems.

Metasponse. This is an incident response framework for executing actions on multiple remote hosts from a central workstation. It provides an easy-to-use job building interface that guides the user through the incident response process in a fire-and-forget manner. The framework provides users with an agile, modular, and flexible capability to counter targeted nation-state level threats and intrusions. This system is currently deployed and in use by U.S. forces.

Distributed Assured & Dynamic Configuration (DADC). This automated tool for generation, verification, and deployment of secure system/network configurations automatically manages consistent information among configuration tools to reduce errors. Configuration errors currently cause 50 to 80 percent of network vulnerabilities and downtime. DADC has already been installed on several systems within the Air Force.

Ruby Slipper. This effort consists of the development of mission components to support operations in a single common framework where multiple tools work together. A pathfinder prototype developed by AFRL has been delivered to two Air Force organizations to enable risk reduction for future procurement efforts.

Aircraft Avionics Cybersecurity. AFRL is researching methods and technologies to protect aircraft from cyberattack. We have created realistic testbeds, discovered and exploited avionics weaknesses and developed ways to defend against them. The resulting knowledge is documented in a manual that has been shared with more than 75 DoD units, federal agencies and U.S. aircraft manufacturers.

Strategic World-wide Integration Capability/Advanced Capability for Understanding and Managing Effects Networks (SWIC/ACUMEN). This effort improves the Cyber Tasking Order (CTO) process by decreasing the CTO production time by 50 percent and increasing the number of cyber missions generated from 60-75 per week to 100 per day. It also enables near real-time effects-based plan monitoring, forecasting and impact analysis, and plan improvement recommendations.

Assured Communications

AFRL's assured communications S&T portfolio is focused on the innovation, development, and maturation of secure communications, networking, and information management technologies to build a timely, secure, and mission-responsive network of networks. Our work will provide the translation of sensory data into actionable information and assure tailored situational awareness and Command & Control (C2) communications globally. Example efforts include:

Secure Beyond Line of Sight (BLOS) *Communications at Extreme Latitudes via Mobile User Objective System* (MUOS). We have developed and demonstrated secure and reliable communications to assure global reach missions spanning mobility to combat. AFRL and Navy SPAWAR have demonstrated global C2 connectivity in airborne MUOS tests over the Pacific Ocean and southern hemisphere. Further, AFRL successfully conducted the first-ever Antarctic MUOS ground transmissions from McMurdo Station, Antarctica. Voice transmissions, as well as chat and file transfer applications were successfully demonstrated, while real-time Precise Position Location Information (PPLI) was simultaneously streamed over MUOS using existing tactical military radios.

Wideband Communications Links. AFRL is developing a suite of capabilities providing new spectrum availability and maneuverability, enabling the Air Force to cope with a congested and contested spectrum. Multiple communications pathways are being developed for advanced wideband airborne

communications. These technologies will provide an increase of several Gbps throughput for hundreds of ISR platforms that are critical for operations in contested environments.

Netted, Distributed Multi-platform Connectivity. This capability was developed by AFRL in partnership with Navy SPAWAR and it addresses both joint and Air Force needs outlined in several Core Function Support Plans. AFRL continues to advance this capability by developing conformal apertures suitable for airborne platforms as well as network protocols to enable robust, rapid multi-platform connectivity for Command and Control ISR exchange.

Secure Remote Radio Communications & Control for Ground Theater Air Controller System (GTACS). AFRL in-house researchers are developing communication interfaces and remote control software to enable secure remote radio operations. The remote radio system allows VHF and UHF radios used by battle managers to be remotely deployed and operated over existing satellite long-haul communications equipment. Each of the remote radio circuits operates in secure or clear-voice modes and also supports anti-jam functions of the remote radios. AFRL enhancements support Advanced Narrowband Digital Voice Terminal (ANDVT) encryption for UHF SATCOM and high frequency over-the-horizon communications. Our current S&T development will support future software defined radio systems over IP-enabled long-haul communications systems for heterogeneous network functionality.

Wideband HF Robust Communications. AFRL is developing a long-haul (approximately 5,000 mile) system to augment the aging High Frequency Ground Communications System by communicating over a Wideband High Frequency (WBHF) communications system, providing 16 times (16x) the bandwidth of the legacy system with inherent resiliency. The WBHF system will provide C2 messaging to forces in the Pacific Area of Operations, enabling robust, assured connectivity when satellite, underwater cables, and other wired connectivity is lost. A multi-point relay proof-of-concept demonstration with advanced signal processing/communications techniques is planned for 2017.

Spectrum-Agile Communications. AFRL is developing fundamental capabilities to adapt complex waveform parameters in response to rapidly changing operational environments. These parameters include power, bandwidth, modulation, coding, and routing to achieve low probability of intercept, anti-jam, and low latency assured communications. AFRL has lab-demonstrated survivable multi-node networking among cooperative assets reconfiguring network topology and spectrum utilization to overcome congestion and mitigate adversary actions. This fundamental AFRL research has garnered international citation and innovation awards. Ongoing work extends these capabilities to rapidly moving platforms.

Electronic Warfare

The traditional approach to updating U.S. electronic warfare (EW) systems has been based on a Cold War industrial model that is neither responsive nor effective. In order to stay ahead of the refresh rate of adversary systems, a new paradigm is needed that moves beyond the parametric-based classification, identification and the pre-programmed countermeasure response that has been used in the past. With this goal in mind, AFRL has been focused on incorporating machine learning into EW systems in an effort called Cognitive EW.

Cognitive EW uses machine-learning research and threat behavior to help classify and identify adaptive threats that have the capacity to change their radar signal attributes such as frequency, pulse repetitive interval and pulse-to-pulse signal modulation in near-real time. AFRL is involved with several industry partners to collaboratively pursue this approach.

In June 2015, AFRL and Northrop-Grumman performed a flight test of the Cognitive Mission Computer (CMC) at the NORTHERN EDGE exercise. The CMC is a project to develop a system that can better classify unknown signals based on both parametric data and behavior using advanced machine-learning algorithms. During the flight, the CMC demonstrated an initial capability to classify signals of interest using a real-time live feed from another sensor.

AFRL continues to develop cognitive EW capabilities with industry with the goal of transitioning technology that will be able to detect novel threat signals and adaptively create EW countermeasure waveforms in near-real time.

Long Distance Sensing

AFRL continues to push forward the Air Force's state-of-the art in long distance sensing capabilities. With a great depth of knowledge in radio frequency (RF) and electro-optical (EO) sensing, AFRL has demonstrated the ability to both enhance existing sensors and capabilities, as well as bring new ones to life in a timely and affordable way. We are expanding and developing both active and passive technologies in RF and EO disciplines with the capability to sense activity in multiple domains. This push is driven by the need to address current global long-range sensing challenges.

We are driving the capability to persistently sense the dynamics of the RF spectrum via ground, air and space and construct a situation awareness picture capable of responding to an adaptive anti-access/area-denial (A2/AD) environment. This multi-dimensional RF sensing space creates the challenge of correlating all ISR and EW electromagnetic activity with more transparency and low-latency.

Our research and development in signal processing, atmospheric physics, antennas and radar is producing significant improvements in Air Force capabilities to observe targets at long distances. Over-the-horizon-radar (OTHR) is a fairly mature technology benefiting from renewed research and development in these areas. Continued development of ground-based radar systems is offering greatly improved situational awareness of our space-borne assets.

A critical component to U.S. ISR capabilities continues to be passive electro-optical imaging. Using alternate wavelength bands and advanced image processing and enhancement techniques, AFRL has demonstrated, in a rigorous and methodical way, an approach to extend the useful range of airborne imaging ISR significantly well beyond the current state-of-the-art. Current research efforts will expand on this success and extend that capability even further.

The ability to identify critical targets with high confidence is also being extended through AFRL efforts in laser radar (LADAR). LADAR images in three spatial dimensions allow the warfighter to understand the true shape of a target. It greatly reduces confusion caused by partial obscuration common in the modern battlespace and is a key enabler in target recognition needed for autonomous operations. AFRL is working across its directorate boundaries to bring this capability to our 4th and 5th Generation aircraft without loss of current capabilities and with minimal integration.

LADAR also offers the potential to employ techniques commonly used in the RF domain with optical imaging. Such a system will produce 3D imagery with resolution beyond a more conventional system. Through the use of synthetic aperture LADAR, AFRL is pursuing an unparalleled 3D imaging capability for the Air Force.

Hydrocarbon Boost

In support of our nation's engine development efforts, the AFRL Hydrocarbon Boost effort is maturing critical Oxygen Rich Staged Combustion (ORSC) technologies with a technology demonstrator using liquid oxygen/kerosene. Technologies developed in the AFRL Hydrocarbon Boost effort are applicable to the existing range of booster engine thrust classes. As the primary organization responsible for research and development of liquid rocket engines for the DoD, AFRL is advancing state-of-the-art in model-driven rocket design with a "crawl-walk-run" testing approach.

In test campaigns, the Hydrocarbon Boost effort will first conduct systematic testing of individual engine components, followed by testing of the integrated engine system. All testing will be highly instrumented to attain unprecedented understanding of rocket engine operation and enable targeted risk reduction.

The Hydrocarbon Boost effort is planned to complete component level testing by 2019 and integrated engine testing is planned for 2021. However, there have been and will continue to be, transitions to support domestic industry engine development efforts throughout the coming years. Our effort has already provided significant impact to the U.S. rocket industry with direct transitions to multiple companies developing ORSC booster engines.

Munitions

AFRL is investigating new munitions technologies to support advanced capabilities for future platforms including alternate weapons PNT for A2/AD, advanced seekers and automatic target recognition, hypersonic technologies, additive manufacturing of munitions, advanced nano and structural energetics, and counter hard and deeply buried targets. We are also pursuing significant integrated systems demonstrations to support technology transition to emerging acquisitions. These include:

Long-Range Strike Demonstrations assist the Joint Force Commander by providing responsive and persistent capabilities enabling the application of force against a variety of targets, to include time-critical, high-value and heavily defended targets. The High Speed Strike Weapon (HSSW) effort is the centerpiece of this concept. Working in partnership with DARPA, we are developing guidance and ordnance technologies for a family of hypersonic air-launched missiles.

Collaborative Strike Demonstrations use distributed, collaborative and cooperative weapons to provide improved mission effectiveness in an A2/AD environment. By employing validated semi-autonomous capabilities in alignment with human-defined Rules of Engagement, these weapons could collaborate to be more effective than weapons employed independently. Smaller weapons can use cooperation to produce scalable effects that increase the capacity and capability of 5th Generation aircraft. The value of these concepts will be assessed through a variety of simulations, hardware-in-the-loop testing, sub-scale testing and integrated weapon flight demonstrations.

Air-to-Air Munitions Demonstrations for Offense and Defense addresses an over-arching emphasis for advanced air superiority weapons is significant size and weight reduction to increase internal carriage capacity. Integration of advanced propulsion and guidance and control system technologies will expand missile operational envelops both within and beyond visual range. These combined technologies provide the warfighter with the capability to rapidly destroy or neutralize air targets and ground-based air defenses at greater distances from the launch aircraft enhancing survival and mission effectiveness.

Selectable Effects/Low Collateral Damage Demonstrations support several Air Force mission areas by developing, maturing, demonstrating, and transitioning armament technologies. AFRL is providing the

user with operational flexibility across the range of military operations. Some of the key attributes are: effective C2, flexibility in operations, tailored lethality effects, dependability, and interoperability. Technologies from this area are needed to support current, ongoing military operations.

Space Situational Awareness (SSA)

The SSA S&T investments needed to maintain our core Space Superiority and C2 missions are substantial and include research in Assured Recognition and Persistent Tracking of Space Objects, Characterization of Space Objects and Events, Timely and Actionable Threat Warning and Assessment, and Effective Decision Support through Data Integration and Exploitation. AFRL along with Air Force Space Command (AFSPC), work across these areas in cooperation with the DoD, intelligence community, and industry.

We provide technologies to support AFSPC and meet the growing demand to ensure space superiority in the face of new threats. Using both ground-based and space-based collectors and exploring multiple phenomenologies, AFRL innovates, matures and transitions technology to support the Joint Space Operations Center (JSpOC) and Joint Interagency Combined Space Operations Center.

The Air Force's S&T investment is designed to leverage our in-house expertise while engaging with academia, industry and international allies. Examples include the deep space uncorrelated target association problem to improve custody of space objects and reduce the burden on the space surveillance network, better conjunction assessment and re-entry estimation algorithms to reduce collision probabilities and unnecessary maneuvers and infrared star catalog improvement to ease observation calibrations.

Recently, the Automated Navigation and Guidance Experiment for Local Space (ANGELS) effort examined techniques for providing a clearer picture of the environment around our vital space assets through safe, automated spacecraft operations above Geosynchronous Earth Orbit (GEO). Equipped with significant detection, tracking and characterization technology, ANGELS launched in 2014 and transitioned to AFSPC in 2015. It maneuvered around its booster's upper stage and explored increased levels of automation in mission planning and execution, enabling more timely and complex operations with reduced footprint. The Air Force is building on the success of ANGELS by partnering with NASA to enhance the coverage of PNT signals in space at and above GEO altitudes by updating the Global Positioning System (GPS) Space Service Volume (SSV) to support even greater autonomy for newly emerging spacecraft operations.

AFRL's ground assets include two unique approximately 3.5 meter telescopes that it uses to conduct research in characterizing space objects in low earth orbits up to GEO orbits and to support various customers in providing near real-time data on such satellites.

The Starfire Optical Range (SOR) on Kirtland Air Force Base, New Mexico, develops optical sensing, imaging, and atmospheric propagation technologies. As one of the world's premier adaptive-optics telescopes, the SOR is capable of tracking low-earth orbiting satellites. Day and night adaptive optics for Low-Earth Orbit (LEO) objects and closely-spaced-object are two example efforts developing capabilities enabled or enhanced by utilizing the unique SOR infrastructure.

The Maui Space Surveillance System (MSSS) takes advantage of Hawaii's complementary technical, geographical, and atmosphere benefits. The MSSS provides critical data to our space warfighters on the health and status of many satellites. A recent breakthrough is providing outstanding images during daylight hours which allow us to support AFSPC with requested information on short timeframes. The co-location of the AFSPC Space Surveillance Network (SSN) optical telescope on the top of Haleakalā and the contributing sensor status of the MSSS telescopes enables rapid and efficient transition.

AFRL is developing key enabling S&T capabilities for data integration, multi-sensor fusion, space object and event characterization, and threat indications and warning for enhanced SSA. The Air Force's Multi-INT Activity Pattern Learning and Exploitation (MAPLE) suite of tools, already in operational use in the intelligence community, are currently being enhanced to provide advanced multi-intelligence fusion, satellite characterization, and space system behavioral analysis capabilities for "left of the event" recognition of anomalous activities.

Rapid prototype fusion, characterization, assessment, and decision support capabilities have already been successfully demonstrated using passive radio frequency and electro-optical SSA data and are being further developed for planned transition to JSpOC Mission System (JMS) and/or operational BMC2 systems called for by USSTRATCOM.

AFRL is testing next-generation space environmental impact and prediction technologies as part of exquisite global space situational awareness for operations in contested space and A2/AD environments. By building on the extensive space weather expertise, AFRL is opening new opportunities to ensure our ability to operate through space weather events while characterizing the effects of the dynamic space environment.

Space Resilience

The AFSPC *Space Enterprise Vision* (SEV) addresses how the Air Force stays competitive in today's environment by working with commercial and other government partners. Under the SEV, AFRL is directly supporting Air Force Space and Missile Center (SMC) with executing the "rapid prototyping" needed to demonstrate resilient and advance technologies.

AFRL continues to work assured satellite communications that are critical to the warfighter in all aspects of the Air Force core missions. We are also helping the Air Force lead the way in the use of small satellites. Small spacecraft are adaptable, tactically responsive, potential mission gap fillers, and provide reconfigurable constellations at an affordable price point.

Leaning ahead, AFRL has implemented efforts to address, and where possible demonstrate emerging technologies, including:

The *Resilient Bus Evaluation Laboratory* (REBEL) has been stood up to understand how integrated technology solutions and innovative satellite operations can enhance the resilience of U.S. space capabilities. Featuring a high fidelity emulation of a satellite and associated ground system, REBEL enables the integration of new sensors, algorithms, processing, and protection technologies. It enables the simultaneous and synergistic development of technologies and the "operational arts" to ensure critical space mission capabilities.

AFRL, in partnership with NASA and commercial partners, has developed the *Roll-Out Solar Array* (ROSA), which uses passively deployed, composite structural booms and a flexible solar cell blanket. ROSA's innovative architecture beats the current state-of-practice rigid solar arrays in all areas of performance. Space Systems Loral will use ROSA to replace its existing arrays for 37 GEO/LEO communications satellites in production.

The *Navigation Technology Satellite-3* (NTS-3) flight experiment is AFRL's next major flight experiment and will explore innovative technologies such as On-Orbit Digital Waveform Generators (ORDWGs), high efficiency amplifiers, and advanced antenna systems. NTS-3 is planned for launch in the early 2020s.

The *Demonstration and Science Experiments* (DSX) space flight experiment, scheduled for launch in late 2017, is centered on demonstrating and maturing technologies to gain better understanding of the MEO space environment and its effect upon satellites.

Additionally, AFRL is testing space craft thermal technologies. We will demonstrate a heat spreader capable of increasing communication bandwidth by supporting higher electronics power loads. Reduced

processor and amplifier temperatures provide for increased functionality/power and improved anti-jamming performance. AFRL has also developed a variety of resilient thermal bus technologies to enable the Air Force to perform agile maneuvering and operate-thru and adjust to unexpected thermal loading events in real-time. Technologies focus on managing the thermal bottlenecks at the component, panel, inter-panel interfaces, and insulation/radiator levels.

Spacecraft Propulsion

Since the 1980's, AFRL has transitioned spacecraft propulsion technologies to most of the nation's National Security Space systems. The latest system to be flying Air Force spacecraft propulsion technology (Hall Effect Thrusters) is the Advance Extremely High Frequency (AEHF) satellite. This technology was recently highlighted when the on-orbit Hall Effect Thrusters had to be used to put the satellite into its proper orbit after the primary orbit raising thruster failed on an AEHF satellite.

More recently, AFRL, the Rapid Capabilities Office, SMC, and industry partners teamed to quickly modify and characterize the XR-5 thruster on the AEHF satellite and test it on orbit using the X-37B reusable space vehicle. The modified XR-5A thruster incorporates modifications to improve performance and operating range.

The Air Force has matured Hall Effect Thrusters and is now researching Field Reverse Configuration thrusters. These multimode thrusters are characterized by highly efficient, low thrust operations. This provides a large dynamic range that extends from station keeping to the high thrust needed for quick maneuvers, all using a single propellant.

Rapid Innovation (Responsive) Technologies

AFRL's Center for Rapid Innovation (CRI) exploits state-of-the-art technology in novel ways to provide affordable and suitable solutions for urgent operational needs. Under AFRL's proven Rapid Innovation process, critical operational needs from warfighters, system program offices, or senior military leadership are referred to the Center for Rapid Innovation, with the approval myself as the AFRL Commander.

CRI draws on user, industry, academia, and laboratory subject matter experts to form a multi-disciplinary team tailored to the nature of each problem. The team analyzes the problem in the context of operational procedures, standards, and limitations; and shapes innovative technology options that can be transitioned into the field, typically in 12 to 18 months. This innovation process leverages the breadth and depth of knowledge within the laboratory and its "innovation network" to form a team to work in a rapid prototyping, collaborative, spiral development environment that generates real solutions.

This development process relies heavily on close interactions with the user and frequent design and development spirals, testing, and experimentation to converge on a “just-right” prototype. The process has been successful over its eight year history in providing near term capabilities for critical warfighter gaps, via field testable and deployable prototypes. Often, the user will work with their acquisition agents to pursue programs of record based on these prototypes.

One recent example of the Rapid Innovation process is our Long Endurance Aerial Platform effort, or LEAP. LEAP provides a revolutionary, low-cost, low acoustic signature, persistent aerial ISR capability to address Combatant Command and U.S. Special Forces ISR gaps by converting a proven, fuel-efficient Light Sport Aircraft into an UAS.

LEAP significantly bends today’s ISR cost-performance curve and enables needed counter-insurgency capability and ISR capacity at a fraction of the cost of comparably performing systems. Based on the success of these tests, USSOCOM requested, and the Office of the Undersecretary of Defense for Intelligence (OUSD(I)) funded, an operational evaluation of the system in theater. AFRL procured the hardware for a complete system consisting of four air vehicles and payloads, and deployed the system in early 2016. This system is being operated in conjunction with the USSOCOM user in ongoing overseas operations. The results to date have exceeded expectations. AFRL is discussing transition options with OUSD(I) and USSOCOM, based on these preliminary evaluations.

AFRL also developed Rapid Innovation solutions for AFSPC to enhance SSA for geostationary orbits, leveraging advanced algorithms to develop orbital tracks and solutions for the population of smaller GEO objects and providing timely detection of changes in those populations. AFRL developed the Search and Determine Integrated Environment (SADIE) tool, fast orbit propagators based on Picard integration methods, and two multi-hypothesis trackers and correlation engines. These tools were installed in a test environment at the Space Situational Awareness Laboratory (SSAL) to evaluate performance against real-time Space Surveillance Network (SSN) data. This innovative approach has shown significant improvements in accuracy and a reduction in man-power to correlate tracks and develop candidate orbits in collaboration with the Alternate JSpOC at Dahlgren. The outputs of the resulting capability has already been used to find 226 new candidate orbits to add to the space catalog, and its remarkable success has led to an ongoing effort to transition the capability to the Dahlgren Mission Processing System in 2016 for continued operational support.

In addition, AFRL has developed a Rapid Innovation solution for the para-rescue community. These heroic individuals need the ability to lift armored vehicles from uneven sloping shale type terrain to aid in

extrication of casualties in a rescue/recovery situation. AFRL developed a solution that reduces the size and weight of the current equipment, while providing an enhanced lift capability, using advanced fiber reinforced airbags and battery powered compressors. Testing of the first prototypes showed that they met all requirements, and a few minor enhancements and improvements were identified. AFRL completed a second design spiral delivered 10 units for extended user field testing, which has gone very well so far.

EXPERIMENTATION

AFRL's experimentation efforts enables the unfettered exploration of alternatives in future environments and involves operators, technologists, requirements, acquisition professionals, and others collaborating from beginning to end in a truly integrated fashion. Our goal in experimentation campaigns is to enact a series of progressive and iterative activities designed to build knowledge and provide a method to rapidly evaluate capability concepts.

In May of this year, the Air Force established the Strategic Development Planning and Experimentation Office. This office supports the Secretary of the Air Force through the Air Force Materiel Command (AFMC) in providing ECCT support, war-gaming, modeling and simulation, and virtual and hardware prototyping to assess concepts and advanced technologies. The focus of this multi-disciplinary team is to build-in agility and formulate truly innovative strategic choices.

As has been noted by AFMC Commander General Ellen Pawlikowski, development planning is not a new competency for the Air Force, but it is an area that has been allowed to wane in recent years. Programming solutions for capability gaps have become platform-centric, rather than strategy focused. Assessments under the new effort will involve multi-domain, air-space-cyber approaches to solutions.

We support the Air Force in all four of the current pilot experimentation campaigns: Future Attack Capabilities (FAC); Directed Energy (DE); Data to Decisions (D2D); and Defeat Agile Intelligent Targets (DAIT). The D2D and DAIT campaigns are supporting the Air Superiority 2030 ECCT, which leveraged AFRL subject matter experts to assess the current climate and provide recommendations. AFRL is a cornerstone in these experimentation campaigns by providing timely empirical data to enable strategic investment decisions and to reinvigorate the culture of experimentation within the Air Force.

AFRL supports the FAC Experimentation Campaign in characterizing the Air Force's ability to conduct future attack (FA) and explore concepts through experimentation. Our goal is to enhance the joint capability to perform FA in a variety of operational environments and across a range of timeframes. Initial experimentation results demonstrated remotely accessible internet protocol (IP) networks can be used to enhance Tactical Data (Link 16) with National Technical Data and improve FA targeting

identification. Our LVC demos have also helped to improve joint training through FA experimentation. LVC experimentation has connected live A-10, F-16, and AH-60 platforms with virtual MQ-1s in the constructive Modern Air Combat Environment to validate JTAC training benchmarks in a Distributed Mission Operations Network. We are also involved in planning FA munitions experimentation for testing on the range and in a LVC environment. Our efforts are helping to ensure near-, mid-, and far-term weapons development is consistent with future FA mission requirements.

AFRL is also involved in the DE Experimentation Campaign. We are beginning to take the concepts and capabilities out of our laboratories and put them into the hands of the warfighter. We are using constructive and operator-in-the-loop simulations to understand the interplay of technologies, concept of operations (CONOPS), and doctrine in close collaboration with operators and technology developers. A related effort involves experimentation with employment of an air-to-ground HEL weapon system on an AC-130 gunship. This work is in close collaboration with the Air Force Special Operations Command to assess and deepen our understanding of system performance characteristics, airborne platform integration considerations, and CONOPS. The body of knowledge gained through these efforts will identify key risk areas and technology needs to better focus our research and accelerate the realization of HEL capabilities across a range of systems and platforms.

AFRL continues to engage with the operational Air Force in the two additional experimentation campaigns being planned in response to Air Superiority 2030 ECCT direction. The D2D experimentation campaign will explore various concepts to provide the right data to decision-makers in the time and manner required and the DAIT experimentation campaign will explore new technology-enabled concepts to defeat challenging targets.

AFRL Strategic Development Planning and Experimentation will understand and synthesize future warfighting needs and reconcile those with available and potential capabilities, concepts, and emerging technologies. Core development planning functions include formulating and evaluating viable future concepts, defining operational trade space, identifying technology shortfalls and S&T needs, and assisting the operational community in refining requirements.

PROTOTYPING

AFRL engages in prototyping as a valuable tool for development planning and experimentation as it enables evaluation of design, performance and production. Prototyping activities are useful at various levels of technology maturity. Specifically, we use concept prototypes to assess feasibility, development

prototypes to test advanced concepts and integrated capabilities and operational/fieldable prototypes that look toward the production and deployment stage. AFRL engages operational users intimately in need analysis, solution conceptualization, and prototype development to ensure delivery of a suitable prototype that satisfies the user need. We often employ a rapid spiral development process that incorporates experimentation and prototyping to quickly evolve design and incorporate lessons learned during operations.

Our recent efforts in improving Convoy C3 and Situational Awareness have been successful. In response to a request from 20th Air Force and Air Force Global Strike Command, we participated in the first spiral of a convoy communications and situational awareness solution. This system provides a self-configuring, self-healing mobile network that allows the members of a nuclear convoy to share voice and text chat messages, imagery from on-vehicle cameras (including overhead imagery from supporting UH-1N helicopters), moving map displays, and reach-back to a command and control center. In parallel with the system deployment to all three 20th AF missile wings, AFRL implemented product improvements in the system based on lessons learned from a previous Operational Demonstration and Evaluation. The second spiral of the system design has been selected for full-scale development with support from Air Force Global Strike Command and the 20th Air Force.

AFRL also supports the Air Force's Adaptive Engine Transition Program (AETP) through rigorous adaptive engine technology maturation to reduce risk prior to Engineering and Manufacturing Development (EMD). This follows from our effort in the highly successful Adaptive Versatile Engine Technology (ADVENT) and Adaptive Engine Technology Demonstration (AETD) efforts. We will continue to participate in AETP's jet engine demonstration and validation program that will advance designs through extensive ground testing for future integration and flight test.

All of our efforts follow AT&L's BBP 3.0 lead to reinvigorate the use of experimentation and prototyping for the purposes of rapid fielding of technologically advanced weapons systems, providing warfighters with the opportunity to explore novel operational concepts, supporting key elements of the industrial base, and hedging against threat developments or surprises by advancing technology and reducing the lead time to develop and field new capabilities.

WORLD CLASS WORKFORCE

Our most important and most valuable resource continues to be the people who comprise AFRL. The technical talent and innovative spirit of our workforce is singly responsible for the technological

superiority of the Air Force. In order to maintain an agile science, technology, engineering and mathematics (STEM) workforce, AFRL is focused on STEM outreach, using all of our human capital advantages in attracting and inspiring individuals to Air Force STEM careers, leveraging our intellectual capital, and maintaining the STEM workforce via our Laboratory Demonstration (Lab Demo) authority.

STEM Outreach

In May 2014, the Assistant Secretary of the Air Force for Acquisition (SAF/AQ) designated AFRL as the Air Force Executive Agent for K-12 STEM Outreach. In this capacity, AFRL is building a K-12 STEM outreach program that institutionalizes and coordinates STEM outreach throughout the Air Force, leverages industry and other government agencies, promotes diversity, and measures results.

As the Air Force STEM Executive Agent and the lead for Air Force K-12 STEM Outreach Strategy, AFRL is directly supporting Air Force K-12 STEM outreach programs at 26 Air Force installations that have K-12 STEM efforts in their respective communities. In FY15, more than 245,000 students were reached across the 26 sites, with more than 180 activities targeted to underrepresented groups across all Air Force locations.

Air Force K-12 STEM outreach also contributed to the success of the national STEM initiatives like the White House's "National Week at the Labs", CyberPatriot National Finals, StellarXplorers National Finals, USA Science & Engineering Festival, Junior Science & Humanities Symposium and the Tragedy Assistance Program for Survivors (TAPS).

AFRL Community K-12 STEM outreach programs are reaching farther back into the educational system to influence younger STEM students with the intent of establishing a long-term pipeline of diverse research talent headed for AFRL. To build this STEM workforce base we utilize hands-on activities and demonstrations, teacher development, competitions, mentoring and tutoring, science fair support, and programs and events such as the DoD STARBASE Programs, *For Inspiration and Recognition of Science and Technology (FIRST)* LEGO Leagues, *FIRST* Junior LEGO Leagues and *FIRST* Robotics Competitions.

Human Capital Advantages

Development, Retention, Recruiting

A primary goal for AFRL is the recruitment, development, and retention of a diverse workforce that is committed to leading in the discovery, development, and integration of affordable technologies for the nation’s air, space, and cyber space forces. These tenets are critical to AFRL mission support and to building and maintaining the workforce human capital. Programs focused on workforce acculturation,

pre-supervisory development, supervisory development, and continuous leadership development are designed to develop and grow the AFRL workforce. AFRL personnel also participate in formal Air Force career development programs.

AFRL is committed to achieving this goal and maintaining its presence as a world-class technical enterprise for the best and brightest scientific and technical leaders in the world. As part of our recruiting activities, AFRL has created a website (www.TeamAFRL.com) where prospective candidates can learn about AFRL technologies, research areas, and civilian job opportunities. In addition, AFRL has established a University Relations position focused specifically on schools identified as "best-in-class" for particular AFRL core technical competencies. Some other activities the laboratory accomplished in this area include new summer internship programs, the AFRL minority recruiting program and the new AFRL Postdoc Fellowship Program.

The Air Force recently developed a coordinated strategy for engagement with Historically Black Colleges and Universities and other Minority-Serving Institutions (HBCU/MIs) including Tribally Controlled Colleges and Universities, Hispanic-Serving Institutions, Asian-American and Native American and Pacific Islander-Serving Institutions, and Predominantly Black Institutions to support the development of science, technology, engineering, and mathematics (STEM) capabilities in support of Air Force needs and to alleviate competency gaps between HBCU/MIs and traditional research universities. As the research arm of the Air Force, AFRL is responsible for executing this strategy which incorporates several goals and metrics to include increasing the new hires from HBCUs/MIs by three percent over the next three years.

In an effort to retain a skilled workforce, AFRL proactively utilizes a variety of programs and initiatives such as student loan repayments, tuition assistance, the Developmental Opportunities Program (DOP), and retention incentives. Furthermore, this past year AFRL reinstituted exit interviews to gain greater insight to why some individuals may choose to seek opportunities outside of the Laboratory.

AFRL Scholars Program

As a means to identify, recruit and hire top S&T talent in the U.S., AFRL operates the Scholars Program. This program is dedicated to preparing students for leadership positions in STEM fields, through the integration of education and experience in our research and development.

From its inception in 2001 to date, the AFRL Scholars Program has provided internship opportunities for over 1,300 high school, undergraduate and graduate students. Students from across the U.S. benefit from and contribute to the Laboratory through research experiences at AFRL locations including Kirtland AFB,

New Mexico, at the Air Force Maui Optical and Supercomputing (AMOS) site in Maui, Hawaii, Eglin AFB, Florida, and at Wright Patterson AFB, Ohio.

Until 2012, the AFRL Scholars Program was administered by on-site government civilians within the AFRL. In 2013, Universities Space Research Association (USRA) was awarded a multi-year cooperative agreement to execute future scholar programs on behalf of AFRL. USRA's expertise, in partnership with AFRL, provides the Scholars Program with successful processing of security clearances, stipends, management of in-and-out processing, and general facilitation of an outstanding scholar experience.

As part of the Scholars Program, AFRL holds a Career Forum. AFRL partners with both local and national industry-specific employers to give Scholars an opportunity to meet with employers in a small group setting to facilitate informal question and answer sessions, as well as participate in short interviews with employers. Post-internship communication indicates that several Scholars have secured employment in defense-related industries as a result of their participation in the Career Forum.

We plan to expand the Scholars Program to offer year-round internships at Kirtland AFB. We are also considering the possible integration of "hybrid" internships between AFRL and industry partners to continue to collaborate and build AFRL's relationships with the STEM industry.

From survey results 97 percent of AFRL Scholars responded that they would like full time careers at AFRL in the future, 90 percent responded that the program has affected their career decisions and 86 percent responded that they would recommend the internship opportunity to others. Numerous Scholars have been employed by AFRL, government/DoD, and local and national STEM industry employers.

Intellectual Capital

AFRL is home to 3,573 of our nation's best researchers and engineers working across disciplines and geographical locations to address Air Force technology challenges. Our expertise spans across 37 core technical competencies (CTCs) and 109 sub CTCs by leveraging the expertise of 1,096 doctoral and 1,694 master's degrees.

AFRL is committed to being the laboratory of choice for the world's best talent and has established a Human Capital Strategy defining the infrastructure, processes and tools to realize our human capital mission and values. This strategy lays out an approach for developing our people, actively managing the development of targeted talent, capturing and leveraging our organizational knowledge and telling the story of our strategy, priorities and key initiatives.

As part of this strategy, we have stood up an Enterprise Learning Council, with Learning Officers assigned to every technology directorate. Learning Officers serve to assess and develop individuals, teams and the organization and promote the preservation of knowledge through coaching, mentoring and other organizational learning programs.

Each year AFRL sends members of our workforce to Long-term Full-time (LTFT) training to earn advanced degrees in under-resourced disciplines or newly emerging knowledge areas. Over the past five years AFRL has invested over $9 million in developing our intellectual capital through LTFT programs.

For scientists and engineers, professional society conferences are the standard mechanism for staying current and connected to the global disciplinary community. While participation in professional conferences was restricted for several years due to funding, we appreciate your help in restoring this capability. Today, scientists and engineers across AFRL are able to identify and fully participate in the professional societies that bring most value to their particular competency.

AFRL serves as a “treasure trove” of intellectual capital and technology that can be leveraged to bring the necessary advantage to our warfighters, or to meet other major technology needs faced by our federal government or society. A portion of the AFRL intellectual capital is captured as invention disclosures and patents. New, aggressive programs are being developed to commercialize this intellectual property to get it to the warfighter faster, quicker and cheaper.

Beyond intellectual property, our intellectual capital is tapped to meet a variety of needs, both military and civil. Emerging and urgent needs often result in a call for help from our rich pool of intellectual resources. A few recent examples include:

Aircraft Crew Breathing System. A team of AFRL experts developed a standard for aircraft crew breathing systems using On-board Oxygen Generating Systems (OBOGS), in response to hypoxia-like incidents experienced by airmen. The Air Force, in conjunction with the Navy and aerospace industry, developed MIL-STD-3050, which covers the design, integration, certification and sustainment requirements for aircraft crew breathing systems using an OBOGS. The standard now prevents inconsistent application of life-support-system-critical items that include an OBOGS.

Aerospace Mishap Support. AFRL engineers provided critical root cause information and corrective actions on 17 aerospace mishaps (including eight class A mishaps), preserving fleet safety and saving Air Force resources in 2016. AFRL engineers also support the FAA in generating and revising material data bases used in aerospace design and providing additive manufacturing guidance for aerospace components.

Dyess Air Force Base HVAC Duct Collapse. The AFRL Systems Support Division provided the root cause for the collapse and recommendations to update the civil industry specification for duct supports. This specification is now used in building codes nationwide.

Laboratory Demonstration (Lab Demo) Authority

The Lab Demo authorities authorized to the Science and Technology Reinvention Laboratories (STRLs) continue to provide AFRL a more responsive and flexible personnel system through direct hire authorities, broad banding, the contribution-based pay system, simplified job classification, developmental opportunities and voluntary emeritus corps among other unique workforce shaping tools. These authorities have enabled AFRL to successfully attract and retain high quality scientists and engineers.

Delegated position classification and broad banding provide management greater control of the workforce by transferring decision-making authority from an inflexible personnel hierarchy to first line supervisors who know what is needed to accomplish the mission. The Direct Hire authority has enabled AFRL managers to hire scientists and engineers in less than half the time of traditional hiring methods.

The Contribution-based Compensation System provides management the ability to manage employee expectations, focus employee contributions toward mission accomplishment and compensate employees appropriately based on contribution to the AFRL mission. The DOP provides opportunities for AFRL personnel to acquire knowledge, experience, and expertise that cannot be acquired in the standard working environment. These developmental activities not only enhance employees' contributions, but also advance the AFRL mission.

We appreciate the work of Congress to provide continued improvements in personnel authorities. These authorities allow AFRL to be as competitive as possible with industry in attracting top scientists and engineers.

LABORATORY INFRASTRUCTURE

Infrastructure focused on S&T is necessary to support innovation and force modernization. From FY07 to FY16, the AFRL received Congressional support for four Military Construction (MILCON) projects executed across three AFRL sites.

Thanks to the approval of the Congress in FY16, we will soon have a new Space Vehicles Component Development Laboratory. The Component Development Lab will support development of space power generation, solar arrays and photovoltaic cells, space power storage, space vehicle mechanisms (launch

separators and maneuvering components), mechanism controls, space protection including radiation-hardened electronics, and environmental sensors and cryocoolers. This new facility consolidates 11 separate S&T infrastructures and provides four light laboratories, two medium laboratories, and class 1,000 clean rooms required for space vehicle research, development, and experiments.

The FY17 President's Budget includes the proposed construction of an Advanced Munitions Technology Complex on Eglin AFB, Florida. This laboratory facility will provide the capability to support research and development of sub-scale high speed munitions requiring advanced energetics containing nano and conventional materials. This laboratory would be capable of handling and using nano-explosive powders, a much needed DoD capability that does not currently exist in the U.S. today.

As the Laboratory Commander, I am especially appreciative of the authorities which allow me to conduct minor infrastructure projects, known as the "Section 219" authority. This authority has enabled rapid improvements to S&T infrastructure. One important Section 219 project is under construction at our Munitions Directorate. The Site C-86 range implements a variable height tower enabling extended slant range measurements, full access to test range geography, optical turbulence distortion reduction, ground clutter elimination, and high value assets protection from over exposure to the elements in support of research, development, and testing of next-generation weapon seekers. This tower supports the delivery of active and passive seeker concepts to defeat adversaries in A2/AD environments as well as urban target environments and long-range targets. In addition, warfighters from Air Combat Command and Air Force Special Operations Command benefit from the use of this tower in their drive to mature technologies for killing moving targets, testing of hard and deeply buried targets, seeker development, wire-strike avoidance LADAR technique, helicopter burnout solutions, and sniper identification efforts.

We also leveraged our Section 219 authority for the Maui Innovative Space Awareness Laboratory (ISAL). The ISAL is a world-class research facility at the Remote Maui Experiment (RME) supporting the mission of the Air Force Maui Optical and Super Computing Site (AMOS). The facility provides laboratory space to complete experiment preparations, mission equipment testing and staging, and observatory remote operations within one mile of AMOS's primary office complex. This facility greatly reduces the need to complete the nearly 100 mile, 4 hour, round trip commute to the Maui Space Surveillance Site (MSSS) located on top of Mount Haleakala. Furthermore, the facility establishes Maui's first quantum computing lab and testing in support of AMO's supercomputing mission.

CONCLUSION

Chairman, Members of the Subcommittee and Staff, thank you again for the opportunity to testify today on the Air Force Research Laboratory's move toward strategic agility in capability development, the impact of our world-class S&T program (game-changing, enabling, relevant, and rapid technologies), the stand-up of a strategic development planning and experimentation capability, prototyping and leveraging the contributions of our entire world class workforce and infrastructure.