A Threat to America's Global Vigilance, Reach, and Power–High-Speed, Maneuvering Weapons: Unclassified Summary

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Unclassified Summary

Committee on Future Air Force Needs for Defense Against High-Speed Weapon Systems

Air Force Studies Board

Division on Engineering and Physical Sciences

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Preface

In February 1949, a research team led by rocketry pioneer Frank Malina launched a two-stage missile, composed of a captured German V-2 topped by a WAC Corporal sounding rocket, into the skies above the White Sands Proving Ground in New Mexico. On this fifth launch attempt under a project named Bumper, that WAC Corporal rocket became the first manmade propelled object to fly at hypersonic speeds, in excess of five times the speed of sound. That small rocket ushered in the age of hypersonic flight.

By the late 1950s, the United States had established itself as the undisputed leader in high-speed flight. With programs such as the X-15 Rocketplane, the ASSET and PRIME vehicles of the 1960s, and more recently the X-43, HIFiRE, and X-51; in the classroom and in wind tunnels, U.S. researchers have consistently led the world in advancing the science and art of high-speed flight. The expertise that informed those programs pioneered the development of new propulsion systems, aerodynamic concepts, control methodologies, and advanced high-temperature materials. Hard-won knowledge of the hypersonic flight corridor led directly to the successful design of manned and unmanned space vehicles, as well as the warheads of the U.S. nuclear arsenal.

Now, six and a half decades after Project Bumper, the U.S. lead in the technologies of high-speed flight is in question, particularly as it pertains to military applications. Several countries around the world have been quite busy establishing their own capabilities, in many cases building directly on work gleaned from the United States. These countries have recognized the military potential of speed and see it as a promising counter to U.S. capabilities. Their investments have been significant, their advancements notable, and their accomplishments in some cases startling. These countries have made no secret of the *fact* of their interest in hypersonics, nor of their *intentions*. They have taken advantage of data and lessons learned from the United States and have been helped by the start-stop approach to technology development (including canceling programs even after major successes) and inefficiencies in the U.S. acquisition processes. As a result, the Committee on Future Air Force Needs for Defense Against High-Speed Weapon Systems has concluded that the United States may be facing a threat from a new class of weapons that will effectively combine speed, maneuverability, and altitude in ways that could challenge this nation's tenets of global vigilance, reach, and power.

This National Academies of Sciences, Engineering, and Medicine report was commissioned by the U.S. Air Force (USAF) to address the question of what, if any, response would be possible to defend against the threat of high-speed weapons. The committee quickly realized that, while responding to high speed is challenging in its own right, the combination of high speed and the unpredictability of high maneuverability poses an even greater hurdle. A lifting-body hypersonic weapon, operating at high altitude but in the sensible atmosphere, could use aerodynamic forces to make its trajectory difficult to predict and even more difficult to interdict. As a result, this report highlights some of the challenges to providing a defensive capability against the combination of speed and maneuverability.

When this study began, the committee hoped to identify a class of technology, or suite of technologies, perhaps even currently in development, for employment against high-speed maneuvering threats. The committee saw many concepts and heard about many different possible approaches, but in the end it concluded that there are no "silver bullets." Stopping a maneuvering hypersonic weapon will be difficult, which is precisely why potential adversaries may be pursuing such systems. More importantly, the committee found that while methods might be developed to defend against one or two incoming threats, traditional approaches in employing defensive measures may be less effective against multiple high-speed maneuvering weapons. As such, the reader of this report will find relatively few concrete recommendations for specific technologies to pursue; rather, it offers the observation that sustained research and development is needed that considers a range of approaches, and those must be pursued in a coordinated and timely manner.

The committee's charter was to focus on *defense*—how the United States could respond when the pointy end is heading toward us. And indeed, the bulk of our analysis has explored defense from both a technology and a roles-and-missions standpoint. But the report also ventures into discussions of developing *offensive* capabilities as well, for both a counter and a defensive response. The committee considers this topic to be within the study's statement of task, for it was made clear in several thoughtful briefings and associated discussions that the best defense, perhaps the only defense, against an opponent's high-speed maneuvering weapon may be another high-speed maneuvering weapon. Offense and defense are two sides of the same coin; as in the days of the Cold War, the only reliable deterrent to the use of a hypersonic weapon may in fact be the threat of a corresponding hypersonic countermeasure that might hold at risk the very sites from which the adversaries' hypersonic strike would originate. To better understand the potential operational capabilities and technical characteristics of such weapons, as well as their potential vulnerabilities, it will be important for the United States to make its own timely investments in this area. To this end, the United States' relatively leisurely pace of disjointed hypersonics technology developments, the lack of diversity in concepts, and the absence of a clear acquisition pathway appear to stand in stark contrast to potential adversaries' feverish pace of research and development and test and evaluation, as well as their broadly cast net of technology options.

Although it was the USAF that asked the National Academies to examine this subject, this report touches on multiple services and organizations within the Department of Defense (DoD). In the committee's view, a future commander may not have the time to debate whether an incoming threat should be addressed by the Army or the Air Force, nor the leisure to deliberate on whether an incoming warhead is technically a ballistic missile or a hypersonic cruise missile. Rather, the organizational roles and missions may need to make the resulting response seamless. To that end, and as this report makes clear, the solution to the high-speed maneuvering weapon threat may depend on a coordinated DoD-wide effort. The committee leaves the specific details of that coordination to others, but offers the view within these pages that potential adversaries are already designing systems that exploit both organizational disconnects and current defensive technical limitations within the United States.

The committee is convinced that the USAF has a critical role to play in developing and employing the possible options to address the challenge of high-speed maneuvering weapons, as well as in providing the intellectual leadership for the DoD and the nation in this field.

Mark Lewis, *Chair*
Committee on Future Air Force Needs for Defense Against
High-Speed Weapon Systems

Statement of Task and Study Approach

The Air Force Studies Board (AFSB) of the National Academies of Sciences, Engineering, and Medicine was asked by the Assistant Secretary of the Air Force for Science, Technology and Engineering to assess the threat of high-speed weapons and recommendations to counter the threat. The National Academies approved the original statement of task for this study in April 2015 and its revision in January 2016 and appointed the Committee on Future Air Force Needs for Defense Against High-Speed Weapon Systems in October 2015.[1] The committee was asked to address the following questions:

1. Review the current and evolving threats, and the current and planned U.S. efforts and capabilities to counter these threats.
2. Identify current gaps and future opportunities where the USAF could provide significant contribution to the U.S. effort to counter high-speed threats.
3. Recommend actions the USAF could take in terms of materiel, non-materiel, and technology development to address the identified opportunities and gaps in U.S. efforts to address these threats.

To address these questions, the committee held four data-gathering meetings, which included face-to-face and telephone interviews, from December 2015 to April 2016 to review, independently research the topic, conduct interviews with experts, identify key findings, and develop recommendations. A fifth meeting was held in May 2016 for the committee to write a classified report of the committee's findings and recommendations. Throughout the course of the study, the committee met with the Air Force Air Combat Command (ACC), Air Force Research Laboratory (AFRL), National Air and Space Intelligence Center (NASIC), Missile Defense Agency (MDA), U.S. State Department, U.S. Pacific Command (PACOM), U.S. Northern Command (NORTHCOM), Defense Advanced Research Agency (DARPA), Air University, Office of the Secretary of Defense (OSD), Naval Research Laboratory (NRL), Sandia National Laboratories, and RAND.

The committee received briefings and reviewed data up to the TS/SCI level in responding to the study statement of task and made every attempt to provide a balanced and fair assessment using the data provided. The following is an unclassified executive summary report.

[1] The appendix provides short biographies of the committee members.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Roger Burg, O'Malley Burg Consulting,
Gillian Bussey, Intelligence Community,
Deems Emmer, Retired Aerospace Engineer,
Conrad Grant, John Hopkins University Applied Physics Laboratory,
Robert Latiff, R. Latiff Associates,
John Montgomery, Naval Research Laboratory,
Henry Obering, Booz Allen Hamilton, Inc.,
William Press, The University of Texas,
Paul Schneider, Independent Consultant, and
David Van Wie, John Hopkins University Applied Physics Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Anita Jones, University of Virginia (emerita), who was responsible for making certain that independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Executive Summary

The following is a summary report that highlights a potential national security threat. The People's Republic of China and the Russian Federation are already flight-testing high-speed maneuvering weapons (HSMWs) that may endanger both forward-deployed U.S. forces and even the continental United States itself. These weapons appear to operate in regimes of speed, altitude, with maneuverability that could frustrate existing missile defense constructs and weapon capabilities.

This new class of HSMWs may in many cases operate in those seams of the U.S. national security organizational structure, creating challenges to effective and timely command and control should they be employed against U.S. forces or the United States itself, as described in Box 1. Put another way, while operational doctrine and command structures adequately address traditional atmospheric air attack or exoatmospheric ballistic missile attack, existing doctrine and organizational structure may not be adequate to address the cross-domain threat posed by HSMWs.

BOX 1
Gaps and Seams

Gaps and seams in organizational and institutional defense can be created through structures, doctrines, geographic and historical responsibilities and cultures.

The United States has an established defense architecture for ballistic missiles: The Missile Defense Agency has a fully structured and established military structure for identifying and responding to ballistic launches: the U.S. Strategic Command. The Department of Defense has integrated combatant commands for responding to threats and managing crises in geographic regions developing and potential launching of intercontinental ballistic missiles. The Intelligence Community has global coverage divided into regional functional and technology areas. All of these agencies and organizations are part of a layered defense architecture for ballistic missiles: detection systems, communications networks, sensors, command and control battle management systems, and integrated battle plans and weapons for response.

In contrast, the committee believes there is no such architecture for high-speed maneuvering weapon (HSMW) defense. HSMWs cross all of these boundaries. They are operational in all military domains: air, sea, land, space, and cyber. They exploit geographic areas and atmospheric space that may not be covered by sensors or detectors. They cross all Combatant Command Area of Responsibility boundaries: U.S. Pacific Command (PACOM), U.S. European Command (EUCOM), U.S. Central Command (CENTCOM), U.S. Northern Command (NORTHCOM), U.S. Strategic Command (STRATCOM), and U.S. Cyber Command (CYBERCOM). HSMWs have the characteristics of both air and space vehicles, and can be either strategic (nuclear) or tactical (conventional) weapons.

It may seem reasonable to dismiss this threat as overblown or non-existent, akin to a 21st century equivalent to the infamous Eisenhower-era "Missile Gap," in part because it has taken decades for this threat to develop. Likewise, it is possible to suggest that a high-speed maneuvering weapon may be defeated by some "silver bullet" solution waiting in the wings. It may even be argued that such systems will never reach operational maturity, given the long and contentious history of hypersonic development and the overpromise that has often characterized the field. However, the value of extreme speed coupled with maneuverability and altitude constitutes a potential threat to U.S. capabilities that should not be discounted or ignored.

In the wake of two world wars, the United States emerged as the world's single most powerful nation. Crucial to U.S. success in the 40-plus years of the Cold War was creating the scientific and technological capability to enable it to reach and project power around the globe, bolstering allies, supporting friends, and confronting aggressors. A central and defining aspect of that capability has been the U.S. integrated land-air-and-sea-based power, empowered by space-based assets.

The nature of the United States air and space power advantage is captured in the Air Force's recognition of "Global Vigilance, Reach, and Power" as the core contributions that the Service brings to U.S. national security. Through the awareness, access, and combat force made possible by U.S. Air Force (USAF) systems, the United States has maintained a robust global presence sustained by air and sea lines of communication and overseen by a rapidly responsive command and control infrastructure. The United States relies on this presence to exercise policy options that support its friends and allies, defend its own national security interests, conduct humanitarian relief, and promote other initiatives.

At the present time, the USAF—and Joint Forces more broadly—are facing an emerging class of threats that could severely challenge global vigilance, constrain global presence, impede global power, and against which current defensive capabilities are inadequate—HSMWs. High-speed maneuvering weapons could pose a challenge to all three core elements of the USAF—and be an impediment to the application of global power in key regions of the planet.

Both the People's Republic of China and the Russian Federation have flown examples of this class of weapon, and other countries have shown interest in many of the underlying technologies for hypersonic flight. As illustrated in Figure 1, HSMWs can fly at high-supersonic (Mach ≥ 3.5)[1] or even hypersonic ($M \geq 5.0$) velocities, maneuver both for deceptive/defensive purposes and to increase their range of attack options, and operate both within and outside the atmosphere, following flight paths that place them beyond conventional ballistic and cruise missile defenses.

Hypersonic speeds can be achieved through two known approaches. The first is a ballistic launch to high speed, typically on a rocket booster, that enables a subsequent unpowered glide trajectory; a vehicle in this class is referred to as a hypersonic glide vehicle (HGV). The second approach is an air launch enabled trajectory of a vehicle propelled by its own rocket, ramjet, or scramjet; such a vehicle would generally be a long-range hypersonic cruise missile (HCM). There are of course hybrid approaches; for example, ballistic boosted vehicles may also be internally powered and thus be considered HCMs. Similarly, a boost glide vehicle could be scaled down and air launched, resulting in a tactical HGV.

[1] Since speed of sound varies with altitude (being approximately 1,100 ft./sec. at sea level and 675 ft./sec. at 100,000 feet), the most common measure of supersonic and hypersonic speed is *Mach number*, named after the Austrian physicist Ernst Mach. Mach number (M) is the velocity of an airplane or missile divided by the speed of sound at the altitude at which it is flying. Mach = 1.0 is the speed of sound, the demarcation between subsonic and supersonic flight; Mach 5 (roughly 1 mile per second) is traditionally considered the lower boundary of hypersonic flight, which extends to orbital velocity up the Mach scale.

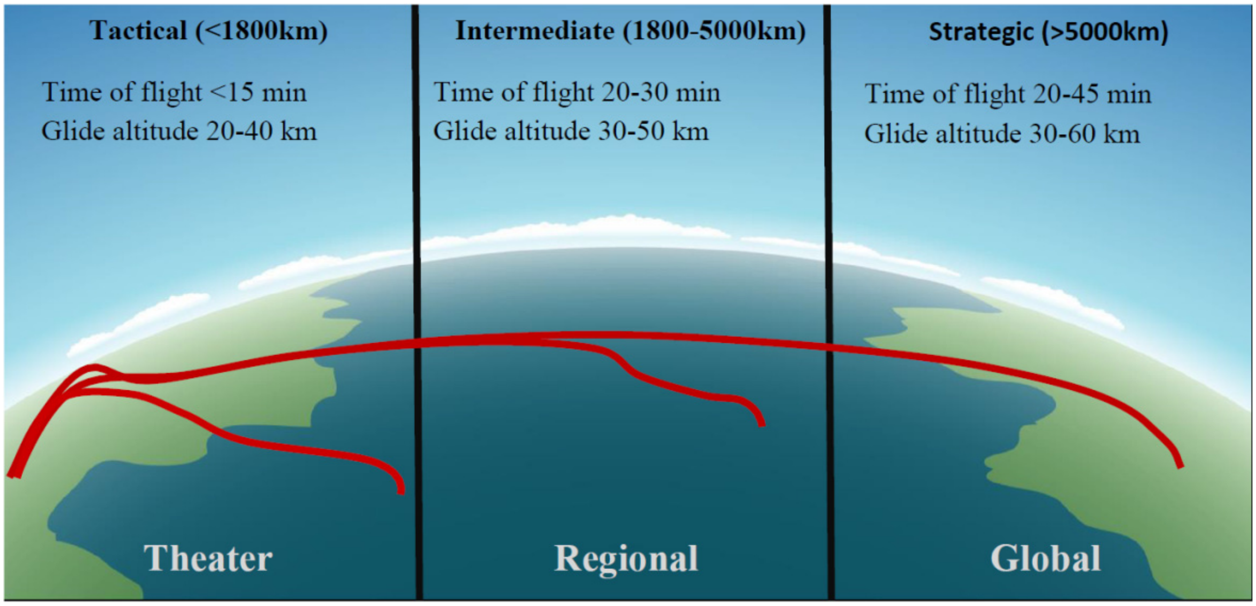

FIGURE 1 Operational flight information for high-speed maneuvering weapons. SOURCE: Adapted from Air Combat Command, "Defense Against High Speed Weapons (DAHSW) Operational Perspective," presentation provided on March 22, 2016.

In addition to flying at high speed through most of their trajectories, both categories of HSMWs will also likely impact their targets at velocities in the high-supersonic (Mach ≈ 3.0-4.0) range. They could maintain significant maneuverability with precision, and thus be capable of engaging fixed or slow moving targets, such as a runway, command and control facility, or a sea-going vessel. Both categories of high-speed weapons may be capable of carrying conventional or nuclear warheads, thereby complicating strategic intent and posture, as well as operational identification, response, and engagement. Both types of systems operate below the classical ballistic missile trajectory and above typical low-speed cruise missile operating altitudes.

The question may be asked, So what? The United States has successfully confronted evolutionary threats before, why is this any different? The answer to this question is the following: HSMWs are not simply evolutionary threats. They are not merely faster or longer-range cruise missiles. Nor are they simply "more maneuverable" reentry vehicles or depressed trajectory ballistic missiles. This is no mere tweaking of an existing threat. Rather, HSMWs can combine speed and maneuverability between the air and space regimes to produce significant new offensive capability that could pose a complex defensive challenge.

The technical challenges posed by HSMWs are compounded. The committee could find no formal strategic operational concept nor an organizational sense of urgency. Further, the committee believes there is a lack of leadership coordination to provide efficiency and direction for the development of possible countermeasures and defensive solutions across the Department of Defense (DoD). If it is to be effective in providing integrated mission direction, that leadership will need to come from a high-level mission-accountable organization within DoD that can address materiel and non-materiel solutions—to include budget authority—across military services, agencies, and the research community. This organization must have responsibilities for development, testing, deployment, integration, and sensors, as well as the battle management command control and communications systems (BMC3) for HSMW. Importantly, to be successful, it will need to have strong ties to the operational community. Considering the nature of the potential threat posed by HSMW systems, the identification of a leadership structure to pursue the actions recommended in this report deserves attention.

As just one example of the degree of integration required, the intrinsic nature of HSMW flight profiles and employment may greatly compress decision and response timelines, which in turn requires any useful countermeasures to be deployed almost immediately. Providing staged responses and avoiding escalations to maximum response will necessitate heuristic processes in the short time window of the HSMW attack. Development of advanced systems may therefore be necessary elements of the command and control doctrine and decision process. The responsible organization will need to take such considerations into account.

A major challenge to organizational leadership is that the development of countermeasures to HSMW systems may fall outside of current mission responsibilities. Defending against HSMWs, while clearly and unequivocally recognized as important by Missile Defense Agency (MDA) leadership, may not be fully addressed because HSMWs are not considered ballistic missiles, even though certain phases of launch and flight can have characteristics similar to those of a ballistic missile. Furthermore, MDA's focus has been on providing an active defense capability with few resources directed toward preemptive and/or counterstrike options. Fortunately, MDA leadership has been very forward-leaning in addressing this situation, and there have been recent positive developments.[2]

Although a detailed analysis of proliferation issues is beyond the scope of this report, it is only logical that pursuing solutions in an integrated manner would provide policy developers a sense of direction, as well as offer the diplomatic community an informed base for integration into international regimes for arms control and deterrence. Further, a visible response to impending threats will demonstrate resolve to both our potential competitors and our own military personnel.

In summary, the ability of the United States to sustain its presence around the world and leverage its global reach is dependent on both U.S. Navy and USAF forward deployment. At a military operational level, HSMWs may impede operations, global vigilance, maintenance, and supporting logistics. At a national strategic level, HSMWs could hold at risk the fundamental U.S. construct of global reach and presence.

[2] Section 1657 of the National Defense Authorization Act for Fiscal Year 2017 Report of the Committee on Armed Services, House of Representatives, on H.R. 4909 directed the Missile Defense Agency to establish a program of record to develop and field a defensive system to defeat hypersonic boost-glide and maneuvering ballistic missiles (May 4, 2016, https://www.congress.gov/114/crpt/hrpt537/CRPT-114hrpt537.pdf).

Appendix

Biographical Sketches of Committee Members

MARK J. LEWIS, *Chair*, is director of the Science and Technology Policy Institute (STPI) at the Institute for Defense Analyses. He went to the STPI directorship from the University of Maryland, College Park, where he was the Willis Young Professor and Chair of the Aerospace Engineering Department. He was chief scientist of the U.S. Air Force in 2004 and held this position until 2008, making him the longest-serving chief scientist in Air Force history. During his tenure as chief scientist, Dr. Lewis expanded basic research support, focused efforts on high-speed flight, sustainment, launch vehicle technologies, and operational space; established major international programs; and was a co-author of the Presidential National Aeronautics Executive Order. Dr. Lewis is the author of some 300 technical publications and is active in national and international professional societies with responsibilities for research and educational policy and support. His research has contributed directly to several programs in the areas of high-speed vehicle and aircraft design. Dr. Lewis is a member of the Air Force Studies Board and Aeronautics and Space Engineering Board of the National Academies of Sciences, Engineering, and Medicine, as well as the Space Technology Round Table. In addition to his service on various advisory boards, he also served as the president of the American Institute of Aeronautics and Astronautics (AIAA). Dr. Lewis holds bachelor degrees in Earth and planetary science, and a bachelors, masters, and doctorate of science in aeronautics and astronautics, all from the Massachusetts Institute of Technology (MIT).

THOMAS R. BUSSING is vice president of the Advanced Missile Systems (AMS), Raytheon. Before joining Raytheon in 2010 as deputy of AMS, Bussing served in the Defense Advanced Research Projects Agency (DARPA) Tactical Technology Office. In that position, he acted as a government venture capitalist responsible for establishing and building virtual companies around enabling technologies and funded programs. While at DARPA, he established programs with a combined value exceeding $400 million. Previously, Dr. Bussing was general manager of Pratt & Whitney's Seattle Aerosciences Center and Pulsedyne, where he was responsible for all financial and technical oversight of the two subsidiaries of the United Technologies Corporation. Before joining Pratt & Whitney, Dr. Bussing was a vice president/general manager with Adroit Systems, Inc., where he was responsible for conceiving, developing, managing, securing capital, managing finances, executing programs, negotiating deals, and transitioning key technologies/products to the Department of Defense (DoD). He started his career in the defense industry in 1985 with Boeing, where he served on several programs, including the national aerospace plane program, the Boeing 777 program, and various classified programs. Dr. Bussing has a bachelor of science with honors in mechanical engineering from McGill University and a master's degree and Ph.D. in aerospace engineering from MIT. He has been awarded 14 U.S. patents and more than 30 international patents. Dr. Bussing was elected on October 1, 2010, as a member of the Air Force Scientific Advisory Board (SAB). He was a member of the 2011 SAB summer study committee evaluating Air Force munitions requirements for 2025 and beyond.

RICHARD HALLION received his B.A. and Ph.D. in history from the University of Maryland. He also graduated from executive training programs at the Federal Executive Institute and the Kennedy School of Government, Harvard University. Dr. Hallion has been a curator at the National Air and Space Museum, Smithsonian Institution; a historian with the National Aeronautics and Space Administration and the U.S. Air Force; a policy analyst for the Secretary of the Air Force; senior advisor for air and space issues, for the Air Force's Directorate for Security, Counterintelligence, and Special Programs; and special advisor for aerospace technology for the Air Force chief scientist. He also serves as a research associate in aeronautics for the National Air and Space Museum and is a member of the board of trustees of Florida Polytechnic University. He is a fellow of the AIAA, a fellow of the Royal Aeronautical Society, and a fellow of the Royal Historical Society.

TERRY J. JAGGERS is chief scientist at Decisive Analytics. Mr. Jaggers is a former Principal Deputy Assistant Secretary of Defense for Systems Engineering (DASD/SE) and former Deputy Assistant Secretary of the Air Force for Science, Technology and Engineering. He graduated from the Industrial College of the Armed Forces with a master's degree in national security, the Florida Institute of Technology with a master's degree in business administration, the University of Illinois, Urbana-Champaign, with a bachelor's degree in aerospace engineering, and Western Illinois University with a bachelor's degree in mathematics. He serves on numerous professional societies and advisory boards, including the University of Illinois Aerospace Engineering Department, the University of Maryland System Research Institute, and the Institute for Defense Analysis' STPI where he provides science, technology, engineering, and STEM workforce advice to the White House Office of Science and Technology Policy. Mr. Jaggers is the owner and president of Excela Ventures Group, which provides technical and management consultation to select national security clients. As chief scientist at Decisive Analytics, he provides strategic advice on systems engineering for major defense acquisition programs the application of target discrimination algorithms for missile defense, battle space awareness, and space situational awareness. Prior to this, he was the director for the Air Force Studies Board and Intelligence Community Programs at the National Academies where he led experts and staff to develop unclassified and classified study reports on a host of strategic national security topics for senior Air Force and Office of the Director of National Intelligence. Mr. Jaggers has been responsible for overseeing the Air Force Research Laboratory's X-51 hypersonic program, launching the inaugural defense against high-speed weapons workshop at the National Academies, participating in a review of U.S. hypersonic test infrastructure for the DoD, and deploying algorithms for real-time joint battle space awareness and fusion of intelligence, surveillance, and reconnaissance.

ERIC KNUTSON is the director of Lockheed Martin Skunk Works-Advanced Projects. He is responsible for maturing seedling programs through executable production programs of both prototype and operationally capable product lines. This is inclusive of all hypersonic vehicle programs such as HTV-2, high-speed programs such as RATTLRS, UAS program, and classified efforts. Additional responsibilities are the creation and deployment of program management processes and leadership development throughout Advanced Development Programs (Skunk Works) distributed sites. He is responsible for the execution of classified prototype and production programs. Primary focus area is in the inception, creation, design, fabrication, and fielding of specialized high technology systems. In this role, he has created and produced 11 different aircraft systems which are currently operational and several additional systems which have been transferred to other areas of Lockheed Martin for continued production and operation. Additional contracts and technologies have been spun off of core work to create several projects and programs, one of which was nominated by the USAF for the Collier trophy award. The success of these programs has been pivotal in Skunk Works receiving the president's National Medal for Innovation. He is a recipient of unit meritorious service award from the U.S. government and the Distinguished Engineering Achievement Award from the national Engineering Council. He was awarded Engineer of the Year and featured on the Military Channel's "Skunk Works" and Discovery Channel's "Jet Engines." He has an M.S. in aeronautics from Embry Riddle Aeronautical University.

RICHARD W. MIES (USN, Ret.) is the CEO of the Mies Group, Ltd., and provides strategic planning and risk assessment advice and assistance to clients on international security, energy, defense, and maritime issues. A distinguished graduate of the Naval Academy, he completed a 35-year career as a nuclear submariner in the U.S. Navy and commanded U.S. Strategic Command for 4 years prior to retirement in 2002. Admiral Mies served as a senior vice president of SAIC as the president and CEO of Hicks and Associates, Inc., a subsidiary of SAIC from 2002-2007. He also served as the chairman of the DoD Threat Reduction Advisory Committee from 2004 to 2010 and as chairman of the boards of the Navy Mutual Aid Association from 2003 to 2011 and the Naval Submarine League from 2007 to 2016. He presently serves as the chairman of the Strategic Advisory Group of U.S. Strategic Command and is a member of the Committee on International Security and Arms Control of the National Academies, the Secretary of Energy Advisory Board, the board of governors of Los Alamos National Laboratory and Lawrence Livermore National Laboratory (LLNL), and the board of directors of BWX Technologies Company, Exelon Corporation, the U.S. Naval Academy Foundation, and the U.S. Naval Institute. He also serves on numerous other advisory boards. Admiral Mies completed post-graduate education at Oxford University, the Fletcher School of Law and Diplomacy, and Harvard University. He holds a master's degree in government administration and international business.

GARY O'CONNELL is a consultant/program manager at SAIC. Mr. O'Connell served as a Defense Intelligence senior leader in the position of chief scientist for the National Air and Space Intelligence Center, Wright-Patterson Air Force Base, Ohio. As chief scientist, he guided the 3,000-person center's analytic production mission, ensuring timely delivery of relevant intelligence data products and services to Air Force and joint operational warfighters, acquisition and force modernization communities, and senior defense and intelligence community policy-making customers. Mr. O'Connell began his government career as a co-op student with the Naval Surface Weapons Center in Dahlgren, Virginia. Upon graduation from the University of Cincinnati, he started work as an air-to-air missile analyst for the Foreign Technology Division, now NASIC. Prior to his appointment as chief scientist, he was the associate chief scientist of the Air and Electronics Directorate, NASIC. Mr. O'Connell received his B.S. in 1981 in aerospace engineering for the University of Cincinnati and an M.S. in aeronautical engineering from the Air Force Institute of Technology in 1986. In 1997, he received an M.S. in national resource strategy from the Industrial College of the Armed Forces, Fort Lesley J. McNair, Washington, D.C., and in 2004 completed the Intelligence Community Senior Leadership Program.

MALCOLM O'NEILL (NAE) served as Assistant Secretary of the Army (Acquisition, Logistics, and Technology); Army acquisition executive, and chief scientist of the Army. Previously, Dr. O'Neill was the chief technical officer of Lockheed Martin Corporation. He served 34 years in the U.S. Army, including two tours of duty in Vietnam. His assignments included DARPA project manager, Talon Gold Space Experiment; deputy project manager, NATO Patriot Air Defense System; project manager, Army Multiple Launch Rocket System; chief of staff, Army Missile Command; and commander of the Army Laboratory Command. He retired as an Army Lieutenant General. In his last uniformed position he served as the director of the Ballistic Missile Defense Organization ("Star Wars"). He holds a Ph.D. in physics from Rice University and is a member of the National Academy of Engineering.

BRIAN R. SHAW is the dean of the School of Science and Technology Intelligence at the National Intelligence University in Washington, D.C. The school is the focus for science and technology (S&T) analytic education, research, and external engagement across the intelligence and international national security communities. He joined the university in 2007 to organize the its S&T Intelligence program, and developed and established the S&T School in 2010. The National Intelligence University was chartered by DoD in 1962, and the university's degrees—the M.S. of strategic intelligence and the B.S. in intelligence—are authorized by Congress. Dr. Shaw received his B.S. from Western Michigan University in 1973, his M.S. from the University of Michigan, Ann Arbor, in 1975, and a Ph.D. from Syracuse University in 1978. His principal areas of study were geology and mathematics. After serving briefly as a lecturer at the University College at Syracuse University, he joined the petroleum industry in a variety of research, development, and exploration positions. He later formed and was the managing partner of an energy-consulting firm in Houston, Texas. In 1991, Dr. Shaw joined the Department of Energy's Pacific Northwest National Laboratory in Richland, Washington, and Washington, D.C. He was a senior advisor in the Field Intelligence Element where he managed several research and special programs. Dr. Shaw was appointed as Deputy National Intelligence Officer for Science and Technology to the National Intelligence Council. Dr. Shaw's primary research focus is on threats to national security arising from globalization of science and technology, evaluating disruptive consequences of adversarial technology adaptations, examining geostrategic resource issues, and identifying frameworks for effective collection, warning, and analysis.

SUZANNE VAUTRINOT (USAF, Ret.) is currently president of Kilovolt Consulting, Inc., a cybersecurity strategy and technology consulting firm located in San Antonio, Texas. She retired from the U.S. Air Force in October 2013 after 31 years of distinguished service, including as Major General and Commander, 24th Air Force, Air Forces Cyber and Air Force Network Operations from April 2011 to October 2013, where she oversaw a multi-billion dollar cyber enterprise responsible for operating, extending, maintaining, and defending the Air Force portion of the DoD global network. Gen. Vautrinot also served as director of plans and policy, U.S. Cyber command and deputy commander, Network Warfare, U.S. Strategic Command (June 2008 to December 2010), and commander, Air Force Recruiting Service (July 2006 to June 2008). She has been awarded numerous medals and commendations, including the Defense Superior Service Medal and Distinguished Service Medal. Gen. Vautrinot is a member of the boards of directors of Wells Fargo, Battelle Board, Ecolab, Inc., Symantec Corporation, and Parsons Corporation. She earned her B.S. from the U.S. Air Force Academy and an M.S. in systems management from the University of Southern California and was a national security fellow at the John F. Kennedy School of Government at Harvard University.

DAVID WHELAN is vice president of engineering with Boeing Defense, Space and Security. Mr. Whelan has responsibility to create, seek out, and explore new technology and business growth vectors for the Boeing Company. Boeing's technology and systems span a wide range of government missions ranging from space systems to airborne systems to ground systems to undersea systems. Both manned and unmanned systems have been developed to solve Boeing's customer challenges. Leveraging his in-depth knowledge of science, technology, systems, and future customer requirements, Mr. Whelan enables Boeing to find new solutions to world's most challenging problems. He serves as a member of the board of directors for Boeing's Madrid Research and Technology Center and HRL Laboratories, the legacy research and development (R&D) laboratory of the former Hughes Aircraft Company, an LLC jointly owned by Boeing and GM. Prior assignments include vice president-general manager and deputy to the president of Boeing Phantom Works, the advanced R&D organization of Boeing, and started his career with Boeing as the chief technology officer for the Space and Communications Group of Boeing. Before joining Boeing, Dr. Whelan served as director of the Tactical Technology Office (SES-5) of DARPA. While at DARPA, he created many legacy joint programs with the Air Force, Navy, and the Army, most notably, the Discoverer II Space Radar Program, the Army's Future Combat System and the Unmanned Combat Air Vehicle. Previously he worked at the Hughes Aircraft Company as program manager and chief scientist for the B-2 Bomber Air-to-Air Radar Imaging Program. He also worked as a physicist for LLNL on X-ray lasers and the Advanced Nuclear Weapons program, and he started his career at Northrop where he was one of the key designers of the B-2 Stealth Bomber and contributed to the YF-23Advanced Tactical Fighter. David earned his Ph.D. (1983) and M.S. (1978) in physics from University of California, Los Angeles; he received his B.A. (1977) from University of California, San Diego. He has numerous publications on electromagnetic radiation, laser plasma phenomena, and defense systems. He holds 14 patents on navigation systems, radar systems, antenna, and low-observable technology. He is currently a member of the National Academy of Engineering, the Air Force Scientific Advisory Board, and the Naval Studies Board of the National Academies. He is standing member of the American Physical Society, the Institute of Electrical and Electronics Engineers, and the AIAA. Dr. Whelan was honored for his government service and received the Secretary of Defense Medal for Outstanding Civil Service in 2001 and the Secretary of Defense Medal for Outstanding Public Service in 1998.