Test and Evaluation Resources

T&E infrastructure must enable credible and comprehensive performance assessments of DOD weapon systems in operationally representative environments.

To keep pace with the expected technological advancements in the modern battlefield, and to adequately test and train U.S. and coalition partner forces in projected multi-domain operational environments, the DOD requires significant and sustained investments in Test and Evaluation (T&E) infrastructure. Specifically, the majority of the Department's open-air test and training ranges and laboratories are outdated and must be modernized to represent and capture the complexities and capabilities of the operational environments of today and the future.

Security regulations, spectrum and range space access constraints, safety considerations, and other limitations, in addition to the sheer cost of live system testing, inherently limit the amount of live testing that is practically achievable. The cost and complexity of hardware-in-the-loop ground-test facilities effectively preclude their development for large-force, multi-domain test and training events. Accordingly, investments are needed to enable solutions to augment the physical test infrastructure with credible digital environments and modeling and simulation (M&S) tools.

Lastly, while the Department recognizes the need to enable T&E of all-domain operations, further investments will expedite the enhancement of test productivity by leveraging and optimizing the benefits of digital engineering tools to standardize data collection and reduction management, as well as data analytics. This section details the specific shortfalls and recommendations in the areas of hypersonics, directed energy weapons, cyber security, nuclear modernization, electromagnetic warfare, space, autonomous and artificial intelligence (AI)-enabled systems, multi-domain operations, common range infrastructure, threat and target surrogates, knowledge management and big data analytics, range sustainability, and the T&E workforce.

Hypersonic Missile and Hypersonic Missile Defense

Hypersonic missiles are designed to achieve speeds between Mach 5 and 20 in the atmosphere, fly distances that can exceed 1,000 miles, and perform extensive maneuvers. The performance evaluation of such systems requires the following T&E capabilities:

- Long-range missile flight test corridors, to include overland corridors
- Range instrumentation sensors to adequately characterize critical aspects of hypersonic flight, from launch, through booster separation and hypersonic vehicle flight with cross-range maneuvers, to impact
- Representative threat targets to adequately evaluate the lethality of U.S. hypersonic missiles
- Foreign missile defense system surrogates (e.g., directed energy weapons, kinetic, countermeasures) to evaluate the survivability of U.S. hypersonic missiles
- Threat hypersonic missile surrogates to evaluate the effectiveness of U.S. defensive capabilities against incoming hypersonic missiles

More detailed shortfalls are included in the Controlled Unclassified Information edition of this report.

Directed Energy

Directed Energy Weapons (DEW) are designed to disable large numbers of adversary targets at fast rates using concentrated energy in the form of high-energy lasers (HEL) or High Power Microwaves (HPM). The DOD needs the following capabilities to safely and effectively test DEW:

- Instrumentation for laser beam diagnostics, to include atmospheric effects on beam properties
- Tools for range safety, satellite deconfliction, and predictive avoidance
- Open-air target boards for measuring laser energy on various targets
- Survivable targets and target instrumentation to evaluate HEL system effectiveness in a measurable, repeatable manner
- A vulnerability data library that includes intelligence-based information regarding target failure mechanisms

The ongoing Mobile High Energy Laser Measurement (MHELM) project is supporting the advancement of these capabilities.

HPM lethal effects focus on disrupting, degrading, or destroying targeted electronic systems or circuits. Narrow-band HPM weapons have greater effective ranges, but prior knowledge of the target characteristics is required to design for optimum radio frequency energy transfer. Wideband HPM systems affect an array of electronic systems but have shorter effective ranges.

Cybersecurity

As the cyber threat continues to exponentially evolve, so must the cybersecurity T&E infrastructure and skilled workforce to adequately assess the cybersecurity posture of developing systems and keep pace with the volume of complex systems and aggressiveness of attacks. There is a need for a structured, coordinated approach for additional resources to develop tools that can automate routine processes to expedite testing, develop M&S tools to estimate cyber effects and complement testing, and work with the Intelligence Community and tool developers to adequately represent the cyber threats. Specifics are included in the Controlled Unclassified Information edition of this report.

Chemical and Biological Defense

The Department lacks a comprehensive approach to countering Weapons of Mass Destruction including Chemical, Biological, Radioactive, and Nuclear (CBRN) threats. Specific challenges continue to be present with the health of the T&E infrastructure required to adequately evaluate the operational performance of the chemical/biological threat detection systems or the survivability of DOD weapon systems against chemical and biological agents. To keep pace with rapid advances in technology, the Department should: 1) develop a long-term strategic solution for the modernization of T&E instrumentation necessary to reduce risk from predicted obsolescence in test instrumentation and data-collection systems; 2) ensure T&E infrastructure and workforce can enable credible and comprehensive performance assessments of DOD chemical/biological detection, protection, and decontamination capabilities in operationally representative environments in support of all-domain operations; and 3) ensure preparation and readiness for testing of aerosolized and vaporized non-traditional agent threats, resulting in reduced risks to force due to halting development and engineering of non-traditional agent safety, security, protection, and decontamination procedures and protocols.

Nuclear Modernization

U.S. Intercontinental Ballistic Missiles (ICBM) and long-range, high altitude ground- and sea-based interceptors are potentially subject to nuclear detonation (NUDET)-generated atmospheric and space environments as depicted in Figure 1. High-altitude NUDET environments could contain X-rays, gamma rays, neutrons, blast effects, and aerothermal heating, depending on the geometry of the operational scenario. X-rays, gamma-rays, and neutrons can kill a missile or space asset kinetically or by creating current pulses in wires that can disable electronics. High-altitude NUDET-generated X-rays and gamma-rays can ionize the upper atmosphere, disrupting radar and communications systems and generating high-altitude electromagnetic pulse (HEMP) effects. In addition, charged-particle bomb debris can be trapped in the Earth's magnetic field, potentially disabling satellites hours to years after the event.

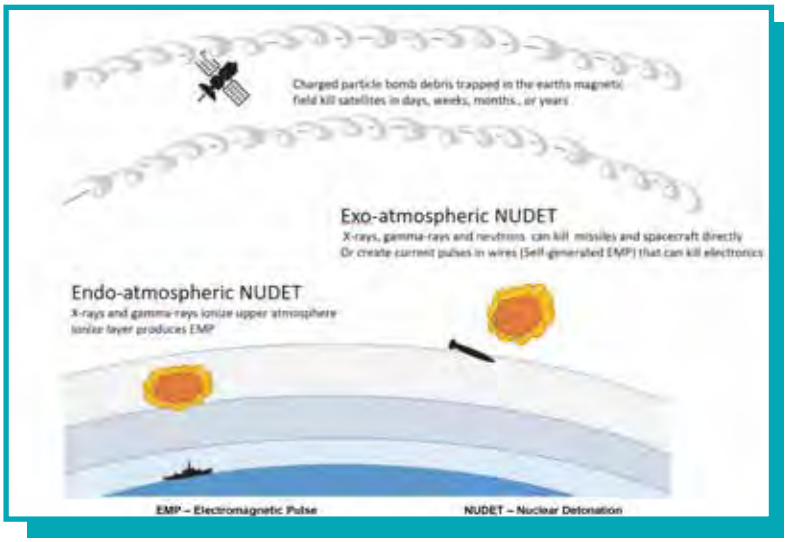

Figure 1. Nuclear Modernization

The DOD needs adequate nuclear effects, ground, and flight test T&E capabilities to collect the test data necessary for the verification and validation of M&S used to conduct nuclear weapon

effectiveness and survivability assessments in a nuclear environment. Additional details are provided in the Controlled Unclassified Information edition of this report.

Electromagnetic Spectrum Warfare

The Electromagnetic Spectrum Operational Environment is increasingly congested and contested by military and civilian systems, and constrained by national and international regulatory changes. Electromagnetic Spectrum Operations (EMSO) comprises the coordinated military actions to exploit, attack, protect, and manage the electromagnetic spectrum environment. Electromagnetic Warfare is a vital element of EMSO and includes Electromagnetic Attack, Electromagnetic Protection, and Electromagnetic Support. The DOD has recognized shortfalls in the infrastructure required to evaluate the performance of weapon systems in a contested, congested, and constrained Electromagnetic Spectrum Operational Environment. Details are included in the Controlled Unclassified Information editions of this report.

In addition, cognitive EMSO systems (incorporating AI technologies to varying degrees) beginning to be developed by the U.S. and its adversaries create unique system attributes: complex, autonomous behavior that will adapt to changing environments as the system learns. These introduce additional T&E infrastructure challenges.

Space

Critical DOD space assets are potentially subject to a range of adversarial attacks, including directed energy weapons, kinetic threats, cyberattacks, electromagnetic spectrum (EMS) fires, and nuclear weapons. To adequately evaluate the survivability of U.S. space systems against such engagements and mitigate any identified vulnerabilities, the Department requires space range infrastructure, instrumentation, and high fidelity-threat surrogates. Details are included in the Controlled Unclassified Information edition of this report.

Autonomous Systems and Artificial Intelligence

Autonomous and AI-based systems are critical enablers in delivering the warfighting capability required to achieve superiority in a multi-domain operational environment. These software-intensive and data-driven systems can learn over time and develop emergent behaviors while integrating with human operators to optimize their contribution to mission success. AI and autonomy will introduce new problems and exacerbate existing ones. T&E of systems that behave flexibly is challenging for many reasons, including covering the large operational spaces and generalizing results to untested scenarios, accounting for how evolving designs, operational use, and environments will alter system effectiveness, or difficulty in defining and measuring success in the first place. Specific challenges include:

- Non-linear, time-varying, and emergent behaviors reduce confidence in fully assessing effectiveness across a range of scenarios/environments.
- Ethical concerns related to lethal decisions may preclude warfighting capability if testing does not confirm exceptionally high confidence in its behavior. Testing for compliance with ethical constraints on behaviors is an open research issue.
- Survivability evaluation of software-intensive systems against adversarial attacks also requires additional research.

Multi-Domain Operations

The rapid proliferation of advanced technology and anti-access and area denial threats have challenged U.S. freedom of action on the battlefield and increased risks to mission effectiveness and kill-chains effects. To achieve and maintain superiority, either sustained or temporary, in an increasingly dynamic, system of systems, joint multi-domain operations environment, U.S weapons systems are being developed and/or upgraded to connect sensors and shooters effectively, efficiently, and securely across all domains using unified command and control networks.

Today's test and training environments are optimized for single-domain evaluations. T&E in multi-domain environments requires sustained investments that will be defined by scenario complexity, mission space needs, representative warfighter networks, multi-level classification, threat emulation, and a complex array of joint supporting battle management test assets. A T&E environment and corresponding tools that allow for credible assessment of combined kinetic and non-kinetic effects across all domains is critical to optimize and correctly evaluate DOD mission effectiveness in the current and future battlefield. Additional details are provided in the Controlled Unclassified Information edition of this report.

Common Range Infrastructure

To keep pace with the technological advancements expected to be found in the modern battlefield the Department should: 1) coordinate the development of credible digital environments and digital twins, 2) connect test and training ranges, 3) virtually link ground test simulation facilities and hardware-in-the-loop testing, 4) pursue common secure networks across test and training ranges in support of operational testing to leverage common live-virtual-constructive integration and real-time monitoring and control of the test, and 5) establish a common or interoperable open-air test and training range infrastructure with common data standards, models, and data collection to facilitate test and training battle shaping requirements. Additional recommendations in addressing specific shortfalls associated with testing hypersonic, directed energy weapons, space, cyber, nuclear, electromagnetic spectrum, and other emerging technologies can be found in respective subsections of this report.

Target/Threat Systems

Threat and target surrogate shortfalls required to adequately evaluate the performance of hypersonic missiles and directed energy weapons (either offensive or defensive), the survivability of our weapon systems and infrastructure against nuclear and EMS fires, and the survivability of critical space assets are discussed in the respective sections in the Controlled Unclassified Information edition of this report. This section is focused on threat and target surrogate shortfalls needed to evaluate the performance of our systems in contested air and sea domains. Details can be found in the Controlled Unclassified Information edition of this report.

Knowledge Management and Big Data Analytics

Knowledge management is a process for transforming information and intellectual assets into enduring value by connecting people with the knowledge they need to act. Creating an effective knowledge management system for meeting T&E needs requires: 1) big data analysis capability to enable efficient search and analyses of large amounts of data, 2) data architectures that make information accessible, and 3) skilled data managers to keep the data organized and accessible.

Integrated and interoperable data collection and test range instrumentation are not optimal for deployed operational testing. The DOD requires an enterprise T&E knowledge management system that securely leverages commercial big data analytic and cloud computing technologies to improve data searchability and evaluation quality, and to reduce decision timelines. It also needs an enterprise approach for T&E of knowledge management systems and implementing an effective mechanism for analyzing data at scales heretofore unimaginable.

The Department has initiated multiple pilot projects to test the capabilities of knowledge management and big data analysis systems against real test data and to inform the development of an enterprise architecture for the test community. However, additional efforts are needed to keep pace with the volume and complexity of T&E data needs.

The Department needs to continue to pursue an evaluation infrastructure, including data architecture, analytics, and skilled Operational Test Agency workforces to meet the data volume and complexity of T&E needs. The Department also needs to establish data analytics to enable data fusion and access across multiple test ranges and domains.

The Operational Test Agency Workforce

The T&E workload has increased dramatically over the last few years due to the rise of software-intensive systems, modern technologies such as autonomous/AI-enabled systems, hypersonics, and directed energy, as well as the increasingly complex and dynamic multi-domain operations environment, which includes advanced maritime, air, land, cyber, space, and electromagnetic spectrum threats. Combined with the demands of innovative, adaptive acquisition framework initiatives, these T&E complexities and changes are straining the T&E workforce. Despite these external demands and challenges, Operational Test Agency plans indicate the workforce will remain largely constant from FY20-28, with two exceptions the Air Force Operational Test and Evaluation Center, and the Defense Information Systems Agency. To address the noted workforce issues, the Operational Test Agencies should:

- Execute a detailed T&E workforce analysis to identify gaps in expertise, capacity, and recruitment needs
- Develop and sustain the execution of the training curricula in specific technical areas, with periodic refresh, to support T&E needs
- Continue to build partnerships with and create reach-back mechanisms to access subject matter experts within key universities, research organizations, and industry as a means to fill knowledge gaps for identified technical areas
- Cultivate and maintain partnerships with key federal (e.g., internal DOD partners, the Intelligence Community, non-DOD federal labs) and international/coalition partners to share lessons learned, ensure operational assessments fulfill requirements, and leverage mutual areas of interest in T&E investments

5G and Radio Frequency (RF) Spectrum for T&E

National spectrum policy supports turning over more spectrum resources to commercial users in frequency bands currently used to support testing and training. This spectrum sell-off is competing with the Department's increased need for additional spectrum as network-centric systems expand. While the Department continues to work with agency partners to develop transition plans to accommodate spectrum sales and joint use policies, there are several concerns that may limit the Department's operational test capabilities. Details are provided in the Controlled Unclassified Information edition of this report.

Wind Farms

The Department has well-established procedures to identify and mitigate any adverse effects of onshore wind turbines on test, training, and operational activities. The proliferation of offshore wind farms on both the East and West coasts, however, raise new concerns that the cumulative effects of multiple offshore wind farms may significantly affect air corridors and the performance of mission essential radars on test and training ranges, as well as surface and subsurface operating areas and transit routes. Offshore wind turbines may also introduce noise and vibration into the surrounding waters, while the cables carrying the generated power to the on-shore collection points may introduce electromagnetic interference along their paths. Noise, vibration, and electromagnetic interference could impact the accuracy of naval sensors (operational and developmental). The DOD and the Bureau of Ocean Energy Management should collect sufficient data to determine any effects of offshore wind turbine noise, vibration, and electromagnetic interference on testing, training, and operational activities to identify potential mitigation techniques.

Other Test and Evaluation Resources Concerns

In FY21, the Services have considered tradeoffs in their FY23 budget that in some cases, if implemented, would degrade their ability to execute adequate operational testing and evaluation. While the proposed budget reductions were neither officially implemented nor certified by USD(R&E) when this report was finalized, proposals like these, in the environment where adversaries continue to increase their technology and T&E capabilities, are ill-advised and should be avoided to prevent the degradation of the performance of our weapon systems in combat.