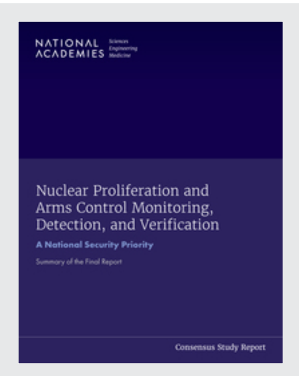

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A National Security Priority

Summary of the Final Report

Committee on the Review of Capabilities for Detection, Verification, and Monitoring of Nuclear Weapons and Fissile Material

Committee on International Security and Arms Control

Policy and Global Affairs

Consensus Study Report

NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

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Acknowledgment of Reviewers

The Consensus Study Report was 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 National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, 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 thank the following individuals for their review of this report:

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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 Alton Romig (NAE Executive Officer, Lockheed Martin [retired]). He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

PREFACE

This report is a summary of the final report of the Committee on the Review of Capabilities for Detection, Verification, and Monitoring of Nuclear Weapons and Fissile Material. Due to the COVID-19 pandemic, the committee addressed the congressionally mandated statement of task in two phases. The first phase, conducted entirely virtually due to pandemic-related restrictions on travel and access to classified information, resulted in an extensive interim report.[1] This interim report addressed much of the statement of task, exploring national and international monitoring, detection, and verification (MDV) capabilities and priorities, and issuing important findings and recommendations that the committee reaffirms in this final report. However, some topics, such as the organization of the mission within the executive branch; some specific MDV capabilities, priorities, and gaps; and the role of the intelligence community across the MDV mission, could not be addressed in the interim report. The committee was also unable to visit key government sites during the first phase of the study to observe operational and research, development, testing, and evaluation (RDT&E) elements of the MDV mission.

The committee began the second phase of this project in August 2021. The composition of the committee and its leadership changed between the two phases. Five members of the original committee stepped down from the committee for the second phase due to time/travel constraints and/or new affiliations, including the original committee chair, Jill Hruby, and original committee vice-chair (and briefly committee co-chair) Corey Hinderstein, who were nominated and confirmed to serve as the National Nuclear Security Administration (NNSA) Administrator and NNSA Deputy Administrator for Defense Nuclear Nonproliferation, respectively. Two new committee members were appointed to ensure that the committee maintained appropriate expertise and balance to carry out the second phase of the study. In this second phase, the committee was able to meet in-person for the first time to have classified discussions and receive classified briefings from key government entities. In addition, committee members were able to visit several important MDV operational and RDT&E sites to better understand the entirety of the MDV enterprise and the challenges facing those carrying out the daily MDV mission and conducting RDT&E to support the mission. COVID-19 continued to present a challenge throughout this phase of the study, forcing the committee to reschedule multiple meetings and site visits or to conduct them via secure videoconferencing. The result of the second phase, a final report that reaffirms and complements the interim report, was completed in June 2022 and finalized with classification markings in January 2023. The committee was able to complete the final report (and this public summary of the final report) due to the commitment of its members and project staff with essential support from federal public servants and experts across the nuclear security enterprise. NNSA, and

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[1] National Academies of Sciences, Engineering, and Medicine. 2021. *Nuclear Proliferation and Arms Control Monitoring, Detection, and Verification: A National Security Priority: Interim Report*. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/26088.

David LaGraffe in particular, assisted immensely with navigating the complex and extensive requirements of the study and security review of the final report and summary.

A robust, well-funded, and future-oriented capability to monitor, detect, and verify nuclear proliferation activities is critical to the national security of the United States and its allies. The committee stressed in the interim report and reinforced in the final report that the MDV mission must be a higher national priority with more support and attention than it currently receives. The committee is thus encouraged to see that many of the findings and recommendations from the interim report have gained traction within the MDV enterprise and in Congress. For example, the committee notes that the enterprise has recently increased focus and funding on ensuring future arms control MDV capabilities, and that Congress has expressed interest in the expansion of the MDV test bed program. The committee hopes that its final report will provide additional guidance and further reinvigorate attention to the MDV mission, and that its findings and recommendations will be reviewed and acted on promptly to achieve a sustained and prioritized MDV program that stewards and improves capabilities, meets future capabilities needs, and minimizes surprise.

Sallie Ann Keller, *Committee Chair*

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EXECUTIVE SUMMARY

Robust monitoring, detection, and verification (MDV) capabilities are necessary to provide decision makers with critical information regarding nuclear threats and to support deterrence and nonproliferation by uncovering efforts to clandestinely develop a nuclear capability or enhance an existing capability. The United States has significant capabilities to monitor, detect, and verify nuclear weapons and fissile material production in foreign states, but in order to address future challenges and avoid surprises, these capabilities must be strengthened and maintained through research and development (R&D) and operationalization of new technologies.

Despite the clear importance of the MDV mission, the committee found that the mission is inconsistently and inadequately prioritized across the U.S. government. The distributed nature of the MDV enterprise requires a high level of integration and coordination to prevent dilution of the mission across the many departments and agencies (D/As) that make up the enterprise. Existing interagency planning and coordination efforts are insufficient, incomplete, or unproven for identifying longer-term MDV problem-sets and capability needs, impacting the enterprise's ability to effectively develop and operationalize new MDV technologies.

The committee assessed that current MDV R&D efforts are impressive, but that the R&D enterprise remains insular and could more fully embrace ideas from outside the traditional enterprise as well as truly novel technical approaches to MDV. To keep up with evolving challenges, the committee concludes that the enterprise must seek to both modernize MDV systems and approaches in the near term and revolutionize them in the longer term instead of continuing to make incremental steps forward. Information sharing and fusion of intelligence sources is a key example of an approach with revolutionary potential.

To improve the U.S. nuclear MDV enterprise, the committee recommends several actions, briefly summarized below.

To improve MDV policy, operations, and research, development, testing, and evaluation (RDT&E) integration:

- The National Security Council (NSC) and the Office of Science and Technology Policy (OSTP) should ensure that there is an enduring interagency planning process engaging all relevant D/As to characterize potential future MDV challenges based on the future threat-space and goals. The process should establish and utilize an external advisory board.
- The Department of Defense (DoD) should establish a governance structure to coordinate requirements, capabilities, and budgetary responsibilities within the DoD and other agencies to lead, manage, operate, and sustain the U.S. Nuclear Detonation Detection System.

- NSC and OSTP should facilitate a review of data and information sharing that includes the MDV mission space, and based on this review, issue clear policy direction to drive the elimination of barriers to data and information sharing.

To enhance stewardship of MDV capabilities:

- NNSA should expand and maintain its nonproliferation stewardship and test bed programs.
- DoD and the Office of the Director of National Intelligence (ODNI) should develop a long-term action plan for stewarding MDV operational capabilities. Congress should ensure that this action plan is appropriately funded.

To increase MDV RDT&E efficacy and innovation:

- The MDV enterprise should institutionalize processes for close communication and coordination between R&D partners and ensure that organizations with the responsibility for transitioning technologies are identified and appropriately funded.
- The MDV R&D enterprise should seek to better leverage the Defense Advanced Research Projects Agency and the Intelligence Advanced Research Projects Agency, as well as relevant commercial capabilities, to further the MDV mission.

To improve MDV for the nuclear fuel cycle:

- NNSA should prioritize R&D efforts that enhance the efficiency of safeguards tools and technologies, address advanced/non-traditional fuel cycle activities, improve early proliferation detection, and address authentication and assurance of data and algorithms.
- NNSA should continue to support R&D to improve source term, environmental fate, and atmospheric/aquatic transport models. NNSA should provide researchers with real production facility data to leverage for the proliferation detection mission.

To improve MDV for nuclear weapons test explosions:

- NSC and OSTP should facilitate a forward-looking policy and technical review of space-based MDV capabilities. NNSA and DoD should consider how to leverage emerging capabilities to ensure that future space-based MDV capabilities are responsive to the evolving space environment.
- The United States should continue to support construction, refreshment, and improvement of the Comprehensive Nuclear-Test-Ban Treaty Organization's International Monitoring System.

To improve MDV for arms control:

- NNSA's arms control MDV R&D program should be sustained regardless of the international environment to ensure that the research community is innovating and generating mature technologies that can be deployed when needed.
- The United States should remain active in multilateral engagements and seek to increase bilateral cooperation to jointly develop technologies for arms control and weapons dismantlement, even if this may be to address far future needs.

To better leverage data for the MDV mission:

- MDV organizations should exploit open-source information/data as an important adjunct to unilateral data collection using classified systems.
- As part of an MDV data science plan, NSC and OSTP should oversee an interagency effort led by NNSA to build MDV data pipelines with multi-point data collection and curation. MDV entities should pursue the broad-based adoption of classified cloud computing.

1

INTRODUCTION

Congress tasked the National Academies of Sciences, Engineering, and Medicine (the National Academies) to undertake an independent review and assessment of the United States' capabilities for monitoring, detection, and verification (MDV) of nuclear weapons and fissile material in the fiscal year (FY) 2020 National Defense Authorization Act (NDAA). See Box 1 for the full statement of task.

The study committee released an extensive interim report in April 2021 after an initial phase of data gathering. Following an additional data-gathering period that included examining restricted information unavailable to the committee during the initial phase of the project, the committee produced a final report in January 2023. In that report, the committee reassessed the findings and recommendations made in its interim report and found them to be supported and confirmed by the additional information. This document, the public summary of the final report, reproduces the findings and recommendations from the interim report and includes the committee's commentary regarding many of the interim report findings and recommendations after additional data gathering. This commentary is shown in boxes following the interim report finding/recommendation. In addition, the committee offers a few new findings and recommendations, which are clearly indicated ("NEW" in front of the finding/recommendation indicates that the finding or recommendation is from the final report and does not appear in the interim report). The conclusion from the final report is also included. Finally, included as appendixes to this summary is an illustration of a notional interagency planning and coordination process and additional commentary regarding the data science process.

BOX 1
Study Statement of Task

An ad hoc committee of the National Academies of Sciences, Engineering, and Medicine will review U.S. capabilities for detection, verification, and monitoring of nuclear weapons and fissile material and make recommendations for improving these capabilities.

Specifically, the review will assess and evaluate:

1. the current national research enterprise for detection, verification, and monitoring of nuclear weapons and fissile material.
2. the integration of roles, responsibilities, and planning for such detection, verification, and monitoring within the federal government.

And identify opportunities:

1. to leverage the national research enterprise to further prevent the proliferation of nuclear weapons and fissile material, including with respect to policy, research and development, and testing and evaluation.
2. for international engagement for building cooperation and transparency, including bilateral and multilateral efforts, to improve inspections, detection, and monitoring of nuclear weapons and fissile material, and to create incentives for such cooperation and transparency.
3. for new or expanded research and development efforts to improve detection and monitoring of, and in-field inspection and analysis capabilities with respect to, nuclear weapons and fissile material.
4. for improved coordination between departments and agencies of the federal government and the military departments, national laboratories, commercial industry, and academia.
5. for leveraging commercial capabilities.

The committee will provide a peer-reviewed assessment containing findings and recommendations, a restricted, peer-reviewed assessment containing findings and recommendations, and a public summary of the restricted report.

2

GOVERNANCE OF THE MDV ENTERPRISE

MDV POLICY, OPERATIONS, AND RDT&E INTEGRATION

Finding 1

Responsibility for the MDV mission is distributed across the government, demanding a high level of interagency coordination. However, the interagency process to assess long-term MDV trends and technology needs is largely informal and does not appear to occur on a regular schedule. As a result, there is no meaningful strategic planning process that produces long-term (10- to 20-year) MDV problem-sets and capability needs to guide the whole research and development (R&D) community.

Recommendation 1

The National Security Council (NSC) [and the Office of Science and Technology Policy (OSTP)] should ensure that there is an enduring, interagency planning process with a consistent periodicity to characterize potential future MDV challenges, assess the adequacy of current MDV capabilities to address these challenges, develop strategic guidance for R&D planning, and advocate for funding. The process should involve the following:

a) Conducting regular updates to the Nuclear Defense Research and Development Strategic Plan (every four years), which should contain success metrics and timelines.

b) Establishing an external advisory board to recommend priorities for nonproliferation and arms control MDV R&D. The board should be composed of experts who collectively have familiarity with the government agencies involved in MDV, as well as the national laboratories, academia, industry, and MDV user communities. The board planning horizon should be 10–20+ years. A possible draft charter is provided in Appendix I [of the interim report].

Commentary Regarding Recommendation 1: *A notional example of a robust interagency planning and coordination process that informs the research, development, testing, and evaluation (RDT&E) process is presented in Appendix A.*

The committee notes that it may not be necessary to establish a single overarching process that comprises the entire MDV mission space, so long as every component of the MDV mission space is covered by a robust planning process aligned with national strategy. Multiple planning processes may be as or more effective than an overarching process that is too broad, but distinct processes must be well-coordinated with appropriate communication across these processes. In addition, the NSC and OSTP may not be the appropriate lead for such process(es), but should be responsible for ensuring that such process(es) exist.

The committee further notes that these robust planning process(es) should:

c) Reflect the future threat space;

d) Involve all of the relevant departments and agencies across the MDV enterprise with policy, operations (including maintenance and refreshment), and/or R&D functions;

e) Regularly assess immediate, mid-term, and long-term capability needs to address both proliferation and arms control challenges, looking at the MDV system as a whole to identify key gaps and potential solutions; and

f) Assess how to increase enterprise agility to address emerging MDV threats.

The committee has learned about additional strategic plans/R&D roadmaps that cover aspects of this mission space similarly to the Nuclear Defense Research and Development (NDRD) Strategic Plan. Recommendation 1 (a) should thus not be limited to the NDRD Strategic Plan but apply more generally to relevant interagency or agency-specific R&D plans to ensure that researchers have a clear view of integrated government priorities in this mission space.

NEW Finding 1-2

The Department of Defense (DoD)/Air Force and Department of Energy/National Nuclear Security Administration (DOE/NNSA) have shared responsibility for the U.S. Nuclear Detonation Detection System (USNDS), and the divergent priorities of these agencies have led to significant governance challenges. The committee did not see evidence of timely or sufficient progress from DoD and NNSA toward addressing these governance issues since they were clearly spelled out in a 2018 DoD Inspector General (IG) report. Governance of the USNDS has become further complicated by the introduction of an additional stakeholder following the establishment of the U.S. Space Force.

NEW Recommendation 1-2

The committee endorses the recommendation made in the 2018 DoD Inspector General report for the Deputy Secretary of Defense, in coordination with the appropriate interagency stakeholders, to establish a USNDS governance structure to coordinate requirements and capabilities within the DoD and throughout the interagency, and once the new governance structure is in place, to establish guidance to lead, manage, and operate the USNDS. The committee notes that an implemented solution must also involve coordinating budgetary responsibilities to be effective.

NEW Finding 1-3

Data and information sharing across the MDV enterprise is hindered by governance, legal, classification, organizational cultural, and technical barriers. The MDV enterprise has made insufficient progress toward addressing persistent data and information sharing challenges.

NEW Recommendation 1-3

The NSC and OSTP should facilitate a review of data and information sharing that includes the MDV mission space to assess governance, legal, classification, and organizational culture barriers. Upon completion of this review, NSC/OSTP should release clear policy direction, potentially in the form of a National Security Memorandum or Executive Order, to drive the elimination of these barriers wherever possible.

STEWARDSHIP OF MDV CAPABILITIES

Finding 2

NNSA has taken significant steps since the release of the 2014 Defense Science Board report[2] to ensure that key MDV capabilities are sustained, especially within the DOE complex, with the development of a new Nonproliferation Stewardship Program (NSP) and the establishment of test beds.

a) The NSP recognizes the need for an intentional and systematic approach to maintaining arms control and nonproliferation capabilities within the DOE complex. Sustaining and continuously improving this program will be critical to its success.

b) The test beds are a cost-effective, innovative use of the DOE/NNSA complex to provide research facilities to the nonproliferation and arms control RDT&E community. The vision, communication, and access to the test beds have potential for improvement.

> ***Commentary Regarding Finding 2:*** *The committee notes that NNSA/Office of Defense Nuclear Nonproliferation R&D's (DNN R&D) test bed program has had a largely positive impact on MDV RDT&E but could be more forward looking to address potential future MDV challenges and develop the necessary capabilities and expertise.*

[2] Defense Science Board. 2014. Task Force Report: Assessment of Nuclear Monitoring and Verification Technologies. Arlington, VA: Department of Defense.

Recommendation 2

The nonproliferation stewardship and test bed programs should be expanded where appropriate and maintained as a vigorous part of the DNN R&D portfolio.

a) The NSP annual assessment of capabilities should look forward at least 10 years, be endorsed by the NNSA Administrator, and include input from laboratory/site/plant leaders on key metrics and their assessments.

b) NNSA should better develop and communicate the vision and objectives of the test beds and assess opportunities for expanding access to all relevant parties including academic, commercial, and international partners.

c) DNN R&D should evaluate whether external review or red-teaming would enhance the test beds' effectiveness.

d) Test beds should take advantage of experience from DOE Office of Science user facilities best practices.

Commentary Regarding Recommendation 2: *When expanding the test bed program, NNSA should also:*

e) Ensure that the suite of MDV test beds are focused on current and future MDV challenges in both nuclear weapon states (i.e., vertical proliferation challenges) and non-nuclear weapon states (i.e., horizontal proliferation challenges), and have the flexibility to evolve with changing threats and policy requirements.

f) Assess opportunities to leverage existing facilities (e.g., material processing facilities, nuclear test facilities, etc.) as MDV test beds, potentially through the use of "bridge facilities" that could allow experimentation that is not feasible in the operational facilities themselves.

g) Assess opportunities to utilize virtual test beds that simulate systems or processes to support MDV R&D, incorporating advanced data analytics where appropriate. Such virtual test beds could also be a tool in the development of new physical test beds

NEW Finding 2-2

Stewardship of operational MDV capabilities such as IT, collection, and measurement infrastructures is critically important and currently lacking. Stewarding capabilities that are rapidly approaching obsolescence is often viewed as lower priority across the enterprise than efforts that more directly respond to near-term threats, and as such is often not adequately funded. This lack of stewardship is putting future MDV capabilities at risk.

NEW Recommendation 2-2

DoD and the Office of the Director of National Intelligence (ODNI) should develop a long-term action plan for stewarding MDV operational capabilities, including IT, collection, and measurement infrastructures, which currently are given too low priority in the face of efforts that more directly respond to near-term threats. To prevent putting future MDV capabilities at risk, this action plan should involve a significant recapitalization of capabilities followed by continual investment to stay current with evolving technology. DoD and ODNI should use this modernization effort as an opportunity to incorporate current best practices such as classified cloud computing. Congress should ensure that this long-term action plan for operational stewardship is appropriately funded.

Finding 3

The DNN R&D university consortia have focused a select subset of universities, faculty, and students on the MDV mission space. These consortia ensure five-year funding to the university programs to develop the next generation of experts for the MDV enterprise and have supported hundreds of undergraduate, graduate, and postdoctoral students.

a) The consortia are increasingly engaging forward-looking disciplinary needs of the MDV enterprise beyond nuclear engineering, such as data sciences.

b) The committee believes the consortia are a positive element of MDV sustainment and capability development; however, without benchmarks associated with their metrics, it is difficult to assess whether or not the consortia are successfully meeting MDV enterprise needs.

c) The national laboratories are expected to bear the significant majority of the cost to oversee the integration of student internships, provide training/oversight for students working in nuclear laboratories or with laboratory equipment, and provide staff to mentor students during their time at the laboratory.

Recommendation 3

DNN R&D should continue to fund and seek continuous improvement of the university consortia. In particular, DNN R&D should do the following:

a) Incorporate best practices, including the development of benchmarks similar to other relevant university consortia programs, such as those run by the National Science Foundation or DoD.

b) Ensure that there is a long-term plan for sustaining and evolving the workforce pipeline and research contributions, including how many and what consortia, in balance with other academic engagement.

c) Strengthen the connectivity between the national laboratories and the consortia by more fully involving laboratory researchers in planning and review meetings and providing funding to laboratory researchers to be fully engaged as mentors.

d) Continue to be responsive to changes in the disciplinary needs of the MDV enterprise.

INCREASING MDV RDT&E EFFICACY AND INNOVATION

Finding 4

Challenges persist in transitioning low-technology readiness level (TRL) MDV R&D to operational systems and tools. R&D and operational organizations are limited in their ability to support prototype development and operational test and evaluation in facilities with access to real processes, data, and/or materials. Classification issues, facility access, conduct of operations and safety procedures, and lack of pertinent facilities and materials often make technology maturation complicated, slow, and expensive. These challenges exist for multiple MDV focus areas:

a) NNSA/Office of Nonproliferation and Arms Control (NPAC)'s Office of International Nuclear Safeguards (OINS) works closely with the International Atomic Energy Agency (IAEA) to address IAEA capability needs and mature technologies to the necessary level for IAEA implementation.

b) NNSA/NPAC Office of Nuclear Verification (ONV) plays a key role in the mid-TRL development of arms control technologies. However, there appears to be a lack of formalized communication and coordination between arms control operators (DoD) and technology providers (NNSA). This gap is partially a result of the Defense Threat Reduction Agency (DTRA)/Research and Development Directorate pivoting away from MDV efforts.

c) Coordination between NNSA/DNN R&D and NNSA/NPAC to identify nonproliferation and arms control MDV technologies priorities and transition low-TRL R&D to higher TRLs could be improved.

d) The Air Force Technical Applications Center (AFTAC) faces challenges in transitioning R&D conducted by interagency partners to operational systems and tools for its nuclear explosion monitoring mission. Unlike for international safeguards and arms control MDV, an organization with the mandate, funding, and knowledge to mature MDV technologies for implementation by AFTAC is not evident.

> ***Commentary Regarding Recommendation 4:*** *Regarding 4(c), when coordination does occur between DNN R&D and NPAC, it is largely limited to very specific safeguards and arms control R&D projects.*

Recommendation 4

MDV R&D organizations and operational end users should take steps to address the challenges in transitioning technologies.

a) Needs of operational users should be taken into consideration for projects, especially those at TRL 3 or higher. Operational users should maintain close communications and coordination with the technology providers throughout the technology development and transition process. Connecting operators and developers earlier in the technology development process will ensure that requirements are better communicated and allow for more agile and responsive development if requirements are still uncertain. As the TRL progresses, the operators should provide increasingly specific technical and operational requirements. NNSA should broaden access to key facilities, processes, and materials via streamlined conduct of operations procedures, through the test beds or otherwise.

b) NNSA/DNN Deputy Administrator should institutionalize a process for close communication between DNN R&D and NPAC (both OINS and ONV) to facilitate selection of high-priority innovative ideas and transition of promising safeguards and arms control technologies.

c) To continue DoD's historic and unique responsibilities in arms control and counterproliferation activities, it should appoint a relevant internal organization to help establish requirements for NNSA arms control technology development and testing activities, especially but not solely as they mature (TRL 3 and above). The organization selected should have real-world knowledge about nuclear weapons storage and deployment conditions in the United States and elsewhere and should be well-versed in the experiences and lessons-learned from the DTRA/On-Site Inspection and Building Capacity Directorate inspection teams.

> ***Commentary Regarding Recommendation 4:*** *To alleviate technology transition challenges between AFTAC and its interagency R&D partners, the DoD Undersecretary of Acquisition and Sustainment and the Secretary of the Air Force should provide AFTAC the resources and flexibility needed to transition applicable technologies into operational capabilities.*
>
> *In addition, additional data gathering has made it clear that the process for close communication and transition pathways between DNN R&D and NPAC recommended in 4(b) should be broad and not limited to specific safeguards and arms control R&D projects since R&D products may be applicable for multiple use-cases.*

Finding 5

MDV innovation emerges from work funded by DNN R&D but also through national laboratory Laboratory-Directed Research & Development (LDRD) projects, academia, and the private sector. Rather than consistently funding early-TRL projects in support of MDV priorities, DNN R&D is reliant on the laboratories to support and foster early work before committing resources for ongoing support. This approach risks gaps in availability of innovative solutions to high-priority MDV missions.

Recommendation 5

The MDV R&D enterprise should look for ways to sustainably drive the innovation pipeline for high-priority MDV objectives, while also maintaining channels to identify and build on basic research developed through LDRD at the national laboratories.

a) DNN R&D should consider how to allow greater participation in its innovation portfolio, including from the national laboratories, academia, and industry.

b) DNN R&D should ensure that its university consortia have agility to incorporate new research directions and technologies that may emerge after a consortium is established. DNN R&D should also track how consortia R&D investments are transferred to the national laboratories and industry for further development.

c) DNN R&D and other parts of the MDV R&D enterprise should use the best practices of other government agencies to optimize the use of prize challenges and solicit innovative ideas from researchers outside the traditional MDV mission space, including the use of surrogate datasets.

NEW Finding 5-2

The Defense Advanced Research Projects Agency (DARPA) and Intelligence Advanced Research Projects Agency (IARPA), which have track records of developing transformative technologies, appear to be underutilized resources for the MDV R&D enterprise. These agencies could play an important role in advancing "blue sky" technologies for the MDV mission, especially in the areas of data science, persistent surveillance, and stand-off surveillance. Both DARPA and IARPA also have proven records of engaging the commercial sector, which could be a valuable asset to the MDV R&D community.

NEW Recommendation 5-2

The MDV R&D enterprise should seek to better leverage DARPA and IARPA to further the MDV mission. MDV R&D enterprise leadership should discuss with DARPA and IARPA leadership opportunities to make progress on MDV grand challenges. To ensure that MDV expertise exists at DARPA and IARPA, NNSA should seek opportunities for technical program managers and laboratory scientists to be detailed to DARPA or IARPA.

Finding 6

DNN R&D and the national laboratories have limited engagement with commercial industry, especially in the emerging technologies areas of open-source and data sciences, where data collection and algorithm development are evolving at a rapid pace and have the potential to benefit the MDV mission space.

Commentary Regarding Finding 6: *The committee further notes that limited engagement with the commercial sector is not specific to DNN R&D or the national laboratories, nor to data science technologies, but is a challenge across the enterprise more broadly. The MDV enterprise is insular and does not have mechanisms to fully leverage external solutions, in contrast to other mission spaces.*[a]

[a] *The committee's interim report notes ln-Q-Tel, the Defense Innovation Unit, and DreamPort as examples of government efforts to engage commercial industry. Other examples include the INVNT Office established by U.S. Customs and Border Protection, and U.S. Special Operations Command's SOFWERX.*

Recommendation 6

NNSA, in coordination with the national laboratories, should engage industry to fast-track new data science methods (e.g., algorithms for sparse datasets) into NNSA-relevant testing and potentially into deployment.

a) NNSA should learn how other government agencies have done this successfully (even for classified operations).

b) NNSA should invest in technology scouting to be familiar with developments in the commercial sector that could be applicable to the MDV mission.

Commentary Regarding Recommendation 6: *While opportunities to leverage external data science advancements are particularly prominent, the committee notes that the recommendations above to learn from other organizations and invest in technology scouting will enable the leveraging of commercial advancements for MDV more broadly.*[a]

[a] The committee notes that the FY202l NDAA directed intelligence community agencies to consider using commercial satellite remote sensing capabilities and services before government systems, and FY2022 NDAA directs National Geospatial-Intelligence Agency and the National Reconnaissance Office to develop a plan for establishing an "integrated commercial geospatial-intelligence data program office."

3

TECHNICAL MDV CAPABILITIES AND RESEARCH AND DEVELOPMENT

MDV FOR THE NUCLEAR FUEL CYCLE

Finding 7

Fuel cycle MDV technologies must evolve to keep pace with the expanding universe of nuclear activities, in terms of both emerging technologies and growth in the number of nuclear activities.

a) IAEA resources have remained constant for a number of years despite increasing MDV demands, implying future MDV may be less comprehensive and less frequent unless more efficient and effective MDV techniques are developed.

b) Current MDV technologies and methods were developed to detect traditional uranium-fueled reactors, gaseous centrifuge enrichment plants, and reprocessing facilities. MDV technologies for emerging reactor designs, alternative enrichment techniques, alternative fuels, and small scale, non-traditional approaches to reprocessing need development support.

c) Current MDV paradigms focus on validating declarations, deterring illicit material diversions, and detecting unknown, undeclared activities. Expanding the MDV paradigm to include motivation and early capability development may enhance opportunities to dissuade and/or counter proliferation behavior and encourage responsible, peaceful use of nuclear energy and technology.

> ***Commentary Regarding Finding 7:*** *The committee notes that technologies and techniques developed to support nuclear safeguards may also be applicable to other areas such as arms control MDV and nuclear compliance MDV. This includes emerging techniques such as artificial intelligence/machine learning (AI/ML) and data assurance/authentication measures.*

Recommendation 7

NNSA should prioritize R&D efforts that (a) enhance efficiency, ease of use/deployment, and sustainability of safeguards tools and technologies; (b) address MDV for advanced reactors, non-traditional and emerging enrichment techniques, and small and/or non-traditional reprocessing technologies; and (c) enhance capabilities to monitor and detect early capability development that could be a potential proliferation threat.

> ***Commentary Regarding Recommendation 7:*** *In addition to the above areas, the committee assesses that NNSA should (d) enhance focus on authentication and assurance of data and AI/ML algorithms to support the safeguards mission.*

Finding 8

Understanding and modeling source term mechanisms, the environmental fate, and atmospheric/aquatic transport of proliferation effluents are key to identifying when and where to sample and gaining insight into proliferation activities from analyzed samples. New analytic approaches that concurrently consider results from multiple sampler locations coupled with atmospheric and aquatic transport models can improve the identification of potential source locations.

Recommendation 8

DNN R&D, in coordination with interagency partners, should continue to support R&D to improve understanding of and develop more accurate models for source terms, environmental fate, and atmospheric/aquatic transport. Field tests should be conducted to assess limitations of the models. These efforts will enhance MDV capabilities for both the nuclear fuel cycle and nuclear test explosions and should include the following:

a) Developing models of effluent release processes and mechanisms from both fuel cycle processes (including new and emerging reactor and fuel cycle technologies) and underground nuclear explosions.

b) Developing linked mesoscale and microscale models for atmospheric and aquatic modeling of effluents of interest.

c) Clarifying the effect of temperature, humidity, UV light, and other pertinent environmental factors on effluent species to determine the nature and rate of physical and chemical changes.

d) Developing integrated analytic processes to analyze environmental sampling results from all relevant sampling locations as a network, coupling their temporally resolved results with atmospheric and aquatic transport models can improve plume source location capability.

Finding 9

To enable the application of wide-area environmental sampling (WAES) as a proliferation and nuclear explosion MDV tool, additional work is needed to characterize known sources of radionuclides and regional background variations.

Recommendation 9

DNN R&D, in collaboration with interagency and international partners, should support R&D to characterize known sources of radionuclides of interest and regional background variations to enhance MDV capabilities for both the nuclear fuel cycle and nuclear test explosions.

MDV FOR NUCLEAR WEAPONS TEST EXPLOSIONS

Finding 10

Capabilities for global detection of nuclear explosions have improved since the 2012 National Academies report on the Comprehensive Nuclear-Test-Ban Treaty (CTBT). In particular, (1) diverse International Monitoring System (IMS) monitoring networks are approaching the CTBT entry-into-force requirements; (2) extensive analyses of the signals for the underground explosions at the North Korean test site have introduced new source characterization capabilities such as source discrimination with regional waves, full moment tensor analysis of seismic wave radiation, and fusion of seismic and satellite-based ground deformation measurements; and (3) advanced data analytics are being explored in R&D programs for their potential to improve detection capabilities. However, improving detection sensitivity remains a key challenge, as does improving the yield estimate accuracy for low-yield tests everywhere. In addition, improved transport models for radionuclide back-tracking are needed for high confidence in identification of seismic detections as nuclear explosion sources.

Recommendation 10

NNSA and the Department of Defense should expand support for R&D to improve nuclear explosion detection sensitivity and confidence, as well as yield estimate accuracy. These efforts should include the following:

a) R&D to improve the accuracy of yield estimates from remote measurements for uncalibrated regions of interest and for low-yield explosions at known test sites.

b) R&D to improve detection sensitivity and confidence by developing higher resolution computational transport models (see also Recommendation 8), exploiting all available data sources (including open sources), and fusing radionuclide monitoring observations with source origin data from seismology or other MDV technologies.

> ***Commentary Regarding Recommendation 10:*** *The committee learned additional details about NNSA's on-going ground-based detonation detection R&D efforts. These robust R&D efforts aim to address both (a) and (b) above. Moving forward, NNSA and DoD should continue to assess the need to expand this R&D space to explore both new technologies and methodologies.*

NEW Finding 10-2

The space environment is rapidly becoming more crowded and contested due in part to the surge in commercial activities and the increasing vulnerability of space-based systems to both unintended and intended interference or attack.

NEW Recommendation 10-2

NSC and OSTP should facilitate a forward-looking policy review of space-based MDV to identify and prioritize required capabilities. NNSA and DoD should consider how to leverage emerging capabilities to ensure that future space-based MDV capabilities are forward-looking and responsive to the evolving space environment. In particular:

a) NNSA and DoD/Air Force should explore how to increase resiliency of space-based MDV systems to interference or physical attack.

b) NNSA and DoD should modernize the data processing systems associated with space-based MDV capabilities to take advantage of emerging data analytic technologies.

c) NNSA and DoD should explore opportunities to leverage commercial space capabilities to support space-based MDV operations and RDT&E.

d) NNSA should reduce the demonstration and validation timeline of new space-based capabilities, potentially by leveraging commercial space capabilities.

Finding 11

A fully functioning IMS and broader CTBT verification regime is beneficial to U.S. nuclear explosion MDV efforts.

a) Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) data are being leveraged, and U.S. support for the CTBTO is being sustained despite non-ratification of the CTBT.

b) International participation in analysis of IMS data is active and there is broad international agreement on the following research needs to improve CTBTO capabilities: atmospheric fate and transport, fusing data streams (e.g., radionuclide and seismic data), characterizing increasing background radiation, filling the data gaps that occur when countries intentionally shut down their sensor network or stop reporting data, and developing an effective on-site inspection capability.

Recommendation 11

The United States should continue to support CTBTO IMS construction, technology refreshment, and improved IMS capabilities because a fully functioning IMS is beneficial to the United States.

> ***Commentary Regarding Recommendation 11:*** *While U.S. unilateral MDV capabilities are generally more sensitive to events in areas of U.S. interest, there is significant value in maintaining a system that produces open evidence that can be shared with the international community, both partners and adversaries, in the event of a potential treaty violation or other concerning activity.*

MDV FOR ARMS CONTROL

Finding 12

NNSA has maintained a modest portfolio of work in MDV tools for arms control, some of it focused on warhead confirmation measurement completed collaboratively between the Offices of Defense Programs (DP) and Defense Nuclear Nonproliferation (DNN). Recently, the need has increased for MDV technologies for non-strategic and non-deployed warheads in potential new arms control treaties, and significant technical challenges remain.

a) Warhead confirmation techniques that can be practically deployed, authenticated, and certified, especially with trusted information barriers, are not yet mature and would benefit from test beds in order to compare strengths and weaknesses in standard and real-world conditions.

b) Joint U.S.-U.K. R&D has significantly advanced the ability to detect the passage of plutonium through a portal. However, a comprehensive technical solution to portal monitoring is needed that can detect highly enriched uranium (HEU) and high explosives in addition to plutonium.

c) The next arms control treaties or agreements may need techniques that rely on warhead identifiers or tags, advanced seals, and possibly new warhead confirmation techniques, especially those that could be used in limited access areas like storage sites. New innovative solutions for such scenarios are still needed.

d) Development of methods to manage access to sensitive facilities and data is needed and must involve the operators of the facilities to be inspected.

e) The proliferation of dual-capable conventional/nuclear delivery systems presents MDV technology challenges that demand attention.

Commentary Regarding Finding 12: *Significant technical challenges remain to meet potential future capability needs for arms control MDV. Importantly, the MDV R&D enterprise has not clearly defined what these future mission needs may be. In addition, inconsistent arms control MDV R&D funding in recent years has slowed capability development and put workforce capacity at risk. The committee does note that since the publication of the interim report, NNSA has significantly increased focus on arms control capability development, but it remains to be seen whether this reinvestment will be sustained long-term.*

The committee further assessed that authentication and certification techniques, systems engineering/integration, and concepts of operation (CONOPS) need additional attention to ensure that new arms control MDV techniques and technologies can be operationalized.

Recommendation 12

DNN's program for arms control MDV should be a sustained, core element of its program at all TRLs regardless of the international environment to ensure that the research community is generating and maturing technologies that could be deployed when needed. Collaboration between DP and DNN may be the best way to accomplish some of these efforts.

a) NNSA should establish a U.S. experimental test bed for warhead verification that is accessible to the academic, laboratory, industrial, and international community to safely conduct experiments on real and surrogate materials; help mature technologies; and be subject to red team and white team testing for authentication, certification, managed access, and vulnerability analyses.

b) The NNSA Baseline, Advanced, and Stretch R&D approaches offer a good starting point for investments. However, the Advanced and Stretch research topics will likely take longer to mature. Therefore, the Advanced and Stretch scenarios should be supported in parallel, not in series, with the Baseline work whenever possible.

c) NNSA, in collaboration with DTRA and other interagency partners, should participate in or initiate projects to develop ideas and tools to distinguish conventional and nuclear versions of dual-capable systems for potential future arms control agreements.

Commentary Regarding Recommendation 12: *The committee additionally recommends that:*

d) NNSA, in collaboration with DTRA and other interagency partners, should increase focus on authentication and certification, systems engineering and integration, and CONOPS for arms control MDV.

e) NNSA and interagency partners should look for opportunities to exercise arms control MDV capabilities more frequently, through the test bed and/or via international partnerships and training events. Such exercises are necessary to develop trusted technologies and CONOPS that can be operationalized in a cooperative arms control framework.

While technologies for warhead verification are necessary as indicated in (a) above, the enterprise should continue to think broadly about a wide range of potential arms control MDV technologies in order to be best equipped for an uncertain future. Because future mission needs are unknown, it is critical that the experimental test bed recommended in (a) above be flexible and adaptable. NNSA should engage policy experts to define a range of possible future scenarios to prepare for using the test bed.

In addition, the committee notes that the need to sustain arms control MDV R&D regardless of the international environment remains true in light of the February 2022 Russian invasion of Ukraine.

Finding 13

Through participation in various international efforts, researchers have had opportunities to develop and test MDV techniques and ideas for weapons dismantlement (including warhead confirmation) without revealing sensitive information with other nuclear weapon states and non-nuclear weapon states.

a) The U.S.-U.K., Quad,[3] and IPNDV (International Partnership for Nuclear Disarmament Verification) programs have been productive venues for international exchange and testing of

[3] Established in 2015, the Quad Nuclear Verification Partnership is a collaboration between nuclear and non-nuclear weapon states (United States, United Kingdom, Norway, and Sweden) to work on nuclear dismantlement approaches.

some MDV techniques. NNSA has not always supported laboratory participation in the IPNDV work at the level required for full participation.

b) There have not been persistent bilateral or multilateral R&D efforts on MDV techniques that involve Russia or China.

> ***Commentary Regarding Finding 13:*** *While the international programs noted in Finding 13 (a) have been productive, the committee notes that opportunities to exercise arms control MDV capabilities through these mechanisms have been relatively infrequent, i.e., occurring every four-to-five years.*

Recommendation 13

The United States should remain active in multilateral engagements and seek to increase bilateral engagements to jointly develop technologies for arms control and weapons dismantlement since success ultimately depends on a high level of confidence by both nuclear and non-nuclear states.

a) The United States should re-engage with Russia as soon as possible in joint technical experiments to develop high confidence, authenticatable and certifiable techniques applicable for future warhead MDV.

b) demonstrations to aid both technology maturation and provide transparency.

c) The United States should apply lessons from the U.K., IPNDV, and Quad partnerships to structure active engagements that include all members of the P5.[4]

> ***Commentary Regarding Recommendation 13:*** *As noted in the commentary following Recommendation 12, NNSA and interagency partners should look for opportunities to exercise arms control MDV capabilities more frequently, through the test bed and/or via international partnerships.*
>
> *However, as of May 2022, the committee believes that Recommendation 13(a) is no longer feasible at present in light of the current war in Ukraine. This recommendation should be revisited if and when relations with Russia improve.*

LEVERAGING DATA FOR THE MDV MISSION

Finding 14

There has been a rapid expansion of commercial remote sensing capabilities over the past decade, both in the United States and abroad. A number of advances support improved MDV:

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[4] The five nuclear weapons states recognized by the NPT are the United States, Russia, the United Kingdom, France, and China.

a) Increased spatial resolution, down to approximately 30 cm, supports more definitive analysis and functional site characterization of existing facilities and the discovery of previously unknown sites.

b) Increased temporal resolution enables monitoring of change over time and increases analytic surety.

c) Increased spectral diversity enables better discrimination of sites, effluents, geology, and other objects of interest.

Finding 15

The amount of open-source data is growing rapidly, along with commercial/nongovernmental processing, exploitation, and dissemination of resulting information. Unauthenticated open-source data have value to MDV efforts, particularly if they are being processed and interpreted by trusted entities such as commercial partners or established academics.

Recommendation 14

Each organization in the MDV enterprise should consider open-source information/data as an important adjunct to national technical means (NTM) that can possibly corroborate or enhance NTM data sources, enable international information sharing at an unclassified level, and/or provide tipping and cueing information for tasking of NTM assets.

a) Operational groups should make sure that they have quick pathways to access useful open-source information when events occur.

b) DNN R&D should consider projects to authenticate open-source information independent of or in collaboration with the open-source information provider.

c) DNN R&D should also continue to explore the potential MDV tradespace between less frequent, higher physical resolution and more frequent, lower physical resolution to see if open-source assets can meaningfully improve monitoring persistence.

Finding 16

Advanced data analytics are rapidly emerging techniques with the potential to facilitate earlier proliferation detection and better decision making.

a) Advanced analytics is of interest to many, if not all, of the organizations that support the MDV mission (DOE/NNSA, DoD, intelligence community, national laboratories, military services, commercial industry, and academia).

b) NNSA/DNN R&D has embraced the importance of advanced data analytics to proliferation detection through its data science portfolio and, in particular, by establishing multi-laboratory projects and ventures.

Recommendation 15

Advanced analytics R&D efforts within NNSA should be supported with a sustained program and projects beyond the typical three-year life cycle to allow these efforts to evolve into technology development and deployment efforts that will be of interest to multiple programs and agencies.

Finding 17

Data availability, both labeled and unlabeled, will be the limiting factor in the use of advanced analytics to support the MDV mission. Currently methods are being built from rich U.S. test bed data.

a) To deal with sparse datasets, foundational AI/ML methods need to be developed including the creation and use of synthetic data to train algorithms.

b) Efficient and compliant means to incorporate unclassified information into classified datasets will be essential for maximum data curation and analysis.

c) As these methods move from basic research to practice, they will need to be tested and used in active global scenarios presenting the need for data sharing across organizations and federal departments.

> ***Commentary Regarding Finding 17:*** *The committee found that while there is increasing focus on data science within the MDV enterprise, there is no high-level MDV data science plan outlining goals and priorities, nor sufficient focus on building a robust data science foundation to enable data science tools (e.g., AI/ML) to be fully leveraged for MDV R&D and/or operations. In addition, the MDV enterprise has largely not yet embraced cloud technology.*

Recommendation 16

The NSC [and OSTP[5]] should orchestrate an interagency program to build MDV data pipelines with multi-point data collection and curation, collaborating with international partners where feasible. The committee recommends that the NSC designate NNSA as the lead agency in this effort. This effort should include improving methods for using sparse datasets and physics-based modeling, and the ability to merge unclassified and classified data. Establishing a robust data pipeline will take time and, if started now, may result in being able to support the evolution of the data analytics research in five years.

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[5] Additional data gathering has made clear that OSTP should be significantly involved in this process as well.

***Commentary Regarding Recommendation 16*:** *The creation of MDV data pipelines by NNSA and interagency partners recommended above should occur with oversight from NSC/OSTP and be a component of a data science plan that addresses all components of the data science process outlined in Appendix B. Through this process, NNSA and interagency partners should focus on building a robust data science foundation and infrastructure that includes problem identification, data discovery and ingestion, and data wrangling and assessment. As a component of this effort, NNSA and interagency partners should undertake efforts to catalogue, organize, and actively curate data of relevance to the MDV mission, potentially with the expert support of data librarians/archivists.*

Developing a wholly comprehensive data infrastructure for the MDV enterprise would be an enormous task and is unlikely to succeed. Current best practice using agile development processes is to start small and iterate on success. The initial effort should focus on building a robust workflow for a segment of the mission space, for example, by focusing on a specific MDV issue. Once a robust end-to-end data process is established for a segment of the enterprise, it can be methodically expanded to incorporate additional issues and/or topics and data sources.

To support this data science foundation, the interagency planning and coordination process(es) outlined in Recommendation 1 should prioritize and fund efforts to modernize and upgrade the computing infrastructure for both the MDV RDT&E and operational missions. As part of this effort, MDV entities should pursue the broad-based adoption of classified cloud computing to maintain a modernized infrastructure that will continue to evolve with best practices.

Additionally, NNSA and interagency partners should consider whether a Chief Data Officer would help maintain focus and drive process on building a robust data science foundation.

4

CONCLUSION

The committee was asked by Congress to review U.S. capabilities for detection, verification, and monitoring of nuclear weapons and fissile material and make recommendations for improving these capabilities. The committee addressed this task in two phases, producing an interim report and a final report that together address the full U.S. monitoring, detection, and verification (MDV) mission space. The final report reassessed and confirmed the 16 recommendations issued in the committee's interim report and also offers new recommendations.

Ultimately, the committee found that while U.S. MDV capabilities are significant, the attention and focus given to this mission across the U.S. government is insufficient given the critical importance of MDV for national security. Robust MDV capabilities are essential to provide decision makers with key information regarding nuclear threats, whether early-stage proliferation activities or arsenal advancements. Despite this, the committee saw a lack of focus on the sustainment of core MDV capabilities that support nonproliferation, arms control, and deterrence. The MDV operational enterprise is currently resource and capability limited, and unable to meet all mission requirements. Due to these limitations, MDV for urgent, near-term threats has been prioritized at the expense of longer term, over-the-horizon threats, which risks leaving the United States vulnerable to rapidly evolving or surprise nuclear threats in the future.

The MDV mission is distributed across many U.S. government departments and agencies, and no one organization is responsible for coordinating the enterprise as a whole. This distributed structure is not in of itself problematic, but requires integrated planning and close coordination to ensure that mission needs are being met in an efficient and effective manner. The committee learned about multiple interagency coordination mechanisms that currently exist across the MDV enterprise, but found these mechanisms to fall short of the committee's first recommendation in the interim report, reaffirmed in the final report, that the National Security Council and Office of Science and Technology Policy should ensure that there is an enduring, interagency planning process with a consistent periodicity to characterize potential future MDV challenges based on the evolving threat space and needs.

The committee was largely impressed by the high-quality on-going MDV research and development (R&D). R&D providers at the DOE national laboratories and sites are deeply committed to this mission and seeking to address future capability needs insofar as those needs are defined. While there are several areas in which R&D efforts should be strengthened or expanded to address important capability needs (as outlined in the committee's findings and recommendations), the overall MDV R&D portfolio is robust and appropriately spans the proliferation timeline. The committee notes that consistent focus on addressing both horizontal and vertical proliferation challenges within this portfolio is critical to ensure that key capabilities and skills are maintained. In addition, there are opportunities for increased focus on systems integration/engineering and CONOPS throughout all topic areas.

While impressive, the committee also assessed that much of the current MDV R&D portfolio is evolutionary versus revolutionary in nature, and that the MDV R&D community is just beginning to pursue some more revolutionary approaches to MDV like multi-INT fusion. Such revolutionary thinking may entail the exploitation of additional data streams (which may require increasing comfort with un-curated data), advancements in data analytics, and developing transformative MDV technologies. To bolster innovation, the insular MDV R&D enterprise would benefit from embracing outside ideas from organizations like IARPA and DARPA as well as from the commercial sector. The MDV enterprise must also ensure that these new technologies developed by the R&D community are operationalized and then sustained.

LIST OF ACRONYMS

AFTAC	Air Force Technical Applications Center
AI	artificial intelligence
CONOPS	concepts of operation
CTBT	Comprehensive Nuclear-Test-Ban Treaty
CTBTO	Comprehensive Nuclear-Test-Ban Treaty Organization
DARPA	Defense Advanced Research Projects Agency
DNN	Office of Defense Nuclear Nonproliferation [NNSA]
DNN R&D	Office of Defense Nuclear Nonproliferation R&D (NA-22) [NNSA]
DoD	Department of Defense
DOE	Department of Energy
DP	Office of Defense Programs [NNSA]
DTRA	Defense Threat Reduction Agency
HEU	highly enriched uranium
IAEA	International Atomic Energy Agency
IARPA	Intelligence Advanced Research Projects Agency
IG	Inspector General
IMS	International Monitoring System [CTBTO]
IPNDV	International Partnership for Nuclear Disarmament Verification
LDRD	Laboratory-Directed Research & Development
MDV	monitoring, detection, and verification
ML	machine learning
NDAA	National Defense Authorization Act
NDRD	Nuclear Defense Research and Development (Strategic Plan)
NNSA	National Nuclear Security Administration
NPAC	Office of Nonproliferation and Arms Control [NNSA/DNN]
NSC	National Security Council
NSP	Nonproliferation Stewardship Program [NNSA]
NTM	national technical means
ODNI	Office of the Director of National Intelligence
OINS	Office of International Nuclear Safeguards [NNSA/NPAC]
ONV	Office of Nuclear Verification [NNSA/NPAC]

OSTP	Office of Science and Technology Policy
R&D	research and development
RDT&E	research, development, testing, and evaluation
SME	subject matter expert
TRL	technology readiness level
USNDS	United States Nuclear Detonation Detection System
WAES	wide-area environmental sampling

A

ILLUSTRATION OF A PLANNING AND COORDINATION PROCESS

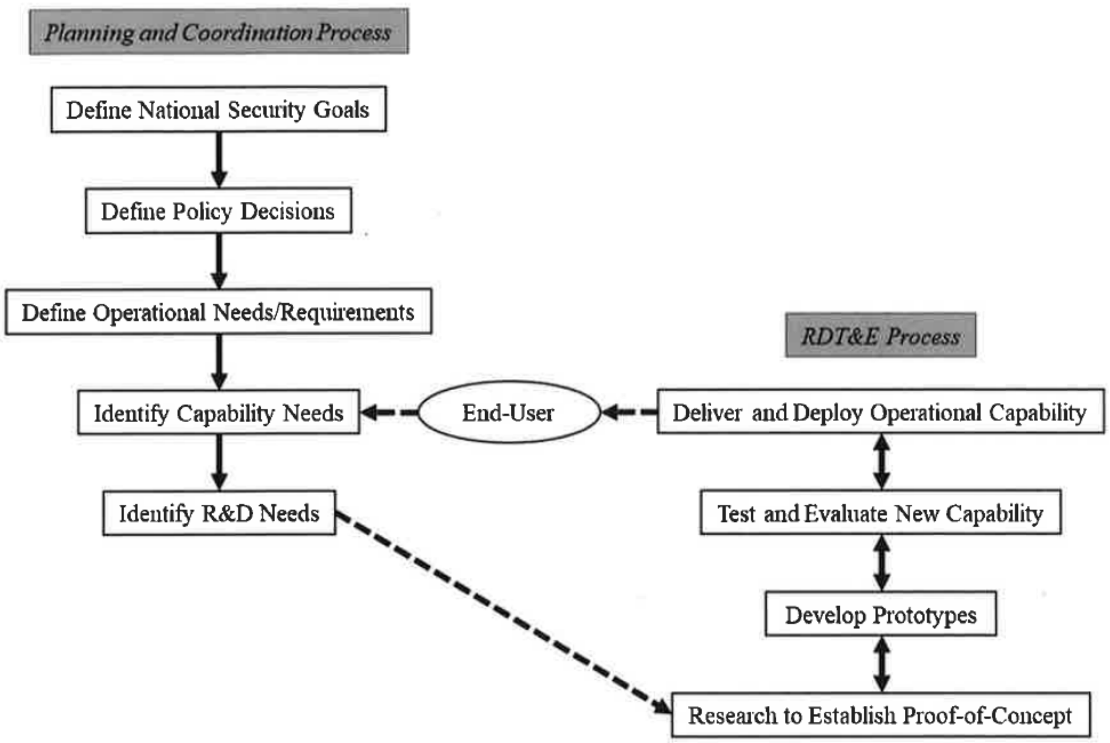

FIGURE A Illustration of a general planning and coordination process and how it relates to an RDT&E process. High-level national security goals will inform policy decisions that in tum define the operational needs or requirements needed to meet the established goals. From there, more specific capability needs can be identified, as well as any R&D necessary to meet those needs. The RDT&E process is thus informed by the planning and coordination process. After research, development, testing, and evaluation, a new operational capability that meets the identified capability needs can be delivered to the end-user, who can provide feedback to the planning and coordination process. Note that the RDT&E is not necessarily linear, as illustrated by the bidirectional arrows.

B

THE DATA SCIENCE PROCESS

As recognition of the importance of data science has grown, the phrase "data science" has become ubiquitous and also used to refer to many different things. To allow for greater specificity regarding data science needs in the MDV enterprise, it is worth deconstructing "data science" and the corresponding roles and responsibilities into its key components.

Fundamentally, data science is the process of bringing data together to address a problem. This process, outlined in Figure B, is not limited to the application of techniques like AI and ML to curated datasets—AI and ML are simply examples of data science tools—but rather starts with the identification of a problem and the discovery of relevant data that can be brought to bear on the problem. Once relevant data is identified, it must be ingested into data management platforms to make it readily accessible to those who need it. From there, data must be processed, cleaned, and assessed for quality and utility before modeling and analyses activities can occur, including more advanced analytical techniques like AI/ML where appropriate. Advanced data analysis has little utility without a robust foundation supporting it.

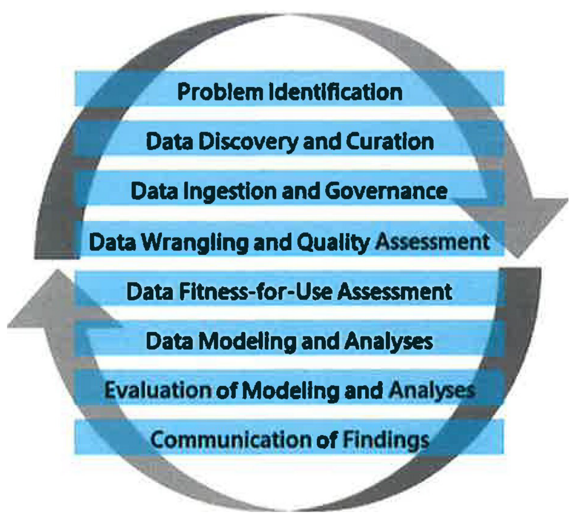

FIGURE B Illustration of the data science workflow.
SOURCE: Adapted from Keller et al. (2020).

It is also important to note that different types of experts—namely, subject matter experts, data engineers, and data scientists—are responsible for different components of the workflow, as described in Box B. The initial steps in the data science workflow—problem identification and data discovery—rely on subject matter experts (SMEs) who understand what questions stakeholders need answered and can determine what data should be collected and how to collect it. Data engineers are responsible for data ingestion and curation and have shared responsibility of data wrangling and assessment with data scientists. Data scientists are also responsible for conducting the modeling and analyses and, in collaboration with subject matter experts, communicating findings to relevant stakeholders.

The workflow shown in Figure B is not linear and requires consistent communication between SMEs, data engineers, and data scientists, as well as reassessment throughout. For example, the findings of one analysis may illuminate opportunities to link data from multiple sources or intelligence modalities. These synergies are key.

BOX B
Data Science Roles

Subject matter experts (SMEs) with MDV experience play a foundational role in the data science process. These scientists and engineers determine what data is necessary to collect based on mission needs, determine where and how to collect such data, and develop the physical systems (e.g., sensors) needed to do so. SMEs also play a critical role in evaluating data models and analyses to ensure that they are logical based on their MDV expertise.

Data engineers/architects develop, test, and maintain data pipelines and architecture (UVA, 2021). In the MDV enterprise, data engineers might build digital infrastructure that collates and stores MDV data from multiple sources.

Data scientists/analysts manipulate data to answer stakeholder questions, often combining data from a variety of sources and sometimes using sophisticated techniques like AI/ML (UVA, 2021). In some cases, data scientists may create or adapt tools for the specific mission. In the MDV enterprise, data scientists might analyze many large MDV datasets from distinct sources (e.g., physical sensor data, pattern-of-life data, open-source publications) to generate additional insights that could not be found by analyzing each dataset independently.

It is worth noting that the committee heard repeatedly from the DOE national laboratories that trained data professionals are in short supply and that the laboratories have difficulty competing with Silicon Valley to recruit talent in this area. This challenge is sometimes addressed by providing MDV SMEs with limited data engineering/science training; however, this is not a sufficient replacement for trained data professionals. The MDV mission needs a cadre of data engineers and scientists that are adequately trained to address relevant data challenges and have a viable career trajectory.

References

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