Nuclear Defense Research and Development Strategic Plan for Fiscal Years 2020–2024

A Report by the

SUBCOMMITTEE ON NUCLEAR DEFENSE RESEARCH AND DEVELOPMENT

COMMITTEE ON HOMELAND & NATIONAL SECURITY

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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About the Subcommittee on Nuclear Defense Research and Development

The Nuclear Defense Research and Development (NDRD) Subcommittee is an interagency group organized under the NSTC Committee on Homeland and National Security. The purpose of the NDRD Subcommittee is to strengthen U.S. nuclear defense capabilities by increasing the operational usefulness, cost effectiveness, and productivity of federally conducted and supported research and development (R&D) efforts in this area. Nuclear defense includes capabilities to prevent nuclear attacks on the United States, allies, and partners; detect nuclear proliferation activities; verify compliance with nuclear-related commitments; and respond to and recover from attacks if prevention fails. The scope of the NDRD ranges from relevant long-term basic science through the technology development cycle to the rapid transition of new technologies supporting NDRD functions.

About this Document

This document was developed by the NDRD Subcommittee, in coordination with National Security Council staff. This document was reviewed by the Committee on Homeland and National Security, and was finalized and published by OSTP.

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Abbreviations and Acronyms

DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DoD	Department of Defense
DOE	Department of Energy
DOS	Department of State
DTRA	Defense Threat Reduction Agency
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
HHS	Department of Health and Human Services
IC	Intelligence Community
NORAD	North American Aerospace Defense Command
NNSA	National Nuclear Security Administration
ODNI	Office of the Director of National Intelligence
USAF	United States Air Force
USN	United States Navy

Use of this Document

The purpose of the Nuclear Defense Research & Development Strategic Plan is to help coordinate Federally-supported nuclear defense research and development (R&D) over the next five years, help identify opportunities to advance nuclear defense R&D priorities, and achieve National nuclear defense policy objectives. The plan covers relevant long-term basic science through the technology development cycle and transition of new technologies supporting NDRD functions. This plan serves as a resource to assist Federal departments and agencies (hereafter, "agencies") in their planning, coordination, identifying high-leverage R&D opportunities, and avoiding unnecessary duplication and redundancy. This strategic plan should help inform the normal budget process through which resources are allocated. Opportunities for R&D adjustments and supplement are considerably greater for the later years of the five-year strategic span, for which budget planning is in earlier stages. All activities are subject to the availability of appropriations.

In some areas within this document, the level of detail is necessarily limited due to classification. Even where high-level R&D planning is not classified, some aspects of implementation and the tracking of progress will require classification controls.

Introduction

The potential for nuclear attack is the most serious threat facing the United States and its allies. Addressing nuclear threats from state adversaries or non-state actors is therefore America's highest defense priority. Under the Trump Administration, national policy documents have articulated a range of threats and risks, and established nuclear defense policy objectives. The 2018 Nuclear Posture Review[1] recognizes that the United States faces a diverse, advanced, and dynamic nuclear threat environment. The 2017 National Security Strategy[2] establishes that "[w]e must prevent nuclear, chemical, radiological, and biological attacks…and protect our critical infrastructure… We must also take steps to respond quickly to meet the needs of the American people in the event of natural disaster or attack on our homeland." To meet the full range of threats, the United States must use all tools available to prevent the spread of nuclear weapons and materials, and to deter the use of nuclear weapons. In the event that deterrence fails, the United States must be ready to defend against and respond to any nuclear attack, and recover from a limited nuclear attack.

America's overall nuclear defense posture integrates activities and capabilities that span five mutually reinforcing elements. These elements work together to prevent nuclear attacks wherever possible and to enable an effective response if ever prevention fails.

Nonproliferation and verification. Nuclear nonproliferation efforts help to prevent state and non-state actors from acquiring nuclear weapons or expanding their nuclear capabilities. The ability to monitor and verify states' compliance with nuclear treaties and agreements helps to limit the spread and growth of nuclear threats.

Detection and attribution. The detection of nuclear and radiological materials, including at borders and in transit, contributes an additional layer of nuclear defense. Technical capabilities that support attribution abilities, such as nuclear forensics, can reveal the sources of nuclear materials and components.

Nuclear deterrence. America's nuclear deterrence policy and capabilities serve to convince adversaries that the United States can respond in ways that would negate any benefit adversaries might seek to achieve by undertaking nuclear attacks on the United States, its allies, or partners, and /or can impose costs that far outweigh any perceived benefit of nuclear attack.

Missile defense. Missile defense capabilities contribute to nuclear defense by limiting the ability of non-peer adversaries to successfully execute missile attacks against the U.S. homeland, U.S. forces abroad, and U.S. allies and partners.

Resilience, response, and recovery. America's overall nuclear defense posture includes the ability to respond effectively to and recover from limited nuclear attacks and incidents. Readiness to manage the consequences of a nuclear detonation to save lives, protect critical infrastructure, property, and the environment, and meet the most basic human needs, is part of greater American resilience.

The five elements of nuclear defense overlap and support one another in direct and indirect ways. Abilities to detect nuclear proliferation and nuclear materials help deter adversaries from the illicit pursuit or transport of nuclear weapons. Capabilities for detection of nuclear materials support

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[1]https://media.defense.gov/2018/Feb/02/2001872886/-1/-1/1/2018-NUCLEAR-POSTURE-REVIEW-FINAL-REPORT.PDF

[2] https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf

nonproliferation and verification efforts. Attribution capabilities help enable effective response to nuclear attack by identifying whom to hold to account, and contribute to deterring adversaries from contemplating covert nuclear attacks or enabling would-be nuclear terrorists or other non-state actors. Missile defense capabilities also contribute to deterrence by helping to convince rogue adversaries that nuclear attacks will not succeed. Missile defense and resilience both contribute to nonproliferation by increasing the range of options available to the United States for responding to nuclear threats and coercion.

As technology progresses and adversaries seek opportunities to threaten and undermine U.S. security, sustaining and advancing an effective U.S. nuclear defense posture requires robust and ongoing research and development (R&D) that supports its five elements. Deliberate and coordinated planning can help ensure that Federally-supported R&D supports the nuclear defense objectives established in National policies. R&D is necessary to sustain and advance U.S. nuclear defense capabilities as threats evolve, technology advances and spreads, and adversaries actively seek to undermine or find weaknesses in U.S. nuclear defense capabilities.

This Nuclear Defense Research and Development Strategic Plan is intended to assist Federal agencies in targeting their R&D efforts over the next five years to support established National nuclear defense policy objectives. It will help agencies to avoid unnecessary duplication, identify interagency gaps, and coordinate a more efficient whole-of-government strategy for R&D investment. This Strategic Plan should inform, but does not replace, agencies' regular planning, programming, and budgeting processes.

This document identifies a set of R&D priorities to help achieve established National policy objectives in each of the five elements identified above. Each R&D priority includes a list of relevant agencies. In many cases, agencies not listed may also contribute to advancing a particular R&D priority.

This Plan will leverage existing efforts and policies while promoting collaboration and integration across the public and private sectors in the United States and abroad. In many cases, agencies are already pursuing or planning R&D consistent with these priorities, details of which can be found in their agency-specific documentation.

Element I: Nonproliferation and Verification

Nuclear nonproliferation and verification of compliance with relevant nonproliferation and arms control commitments are essential aspects of nuclear defense. Preventing the spread of nuclear materials and reducing the number of nuclear weapons in the hands of potential adversaries supports U.S., allied, and partner security. For the purposes of this document, capabilities for detection of proliferation activities other than direct detection of nuclear materials are included in the Nonproliferation and Verification element of America's nuclear defense posture. Capabilities for direct detection of nuclear materials are covered in the Detection and Attribution element.

National policy, as outlined in the National Security Strategy and the Nuclear Posture Review, establishes the following high-level nonproliferation and verification policy objectives to ensure that America can address enduring and emerging challenges in the following areas:

- Predict, detect, and characterize[3] nuclear proliferation and weapons development activities

- Reduce vulnerability and improve security of nuclear and radiological materials around the world

- Provide timely and reliable verification and monitoring of states' compliance with nuclear safeguards and arms control agreements

Nonproliferation and verification efforts support other elements of America's overall nuclear defense posture. For example, abilities to detect nuclear proliferation and nuclear materials help deter adversaries from the illicit pursuit of nuclear weapons.

Interagency R&D Activities

A number of agencies are developing technologies in support of U.S. nonproliferation and verification policy objectives. The National Nuclear Security Administration (NNSA) within the Department of Energy (DOE), executes the majority of U.S. nuclear nonproliferation R&D activities. NNSA leverages the resources and expertise of DOE/NNSA national laboratories, sites and plants, industry, and universities to support long-term investments in scientific innovation that advances U.S. technical capabilities. NNSA's nonproliferation R&D investments focus on the development of technologies up to the proof of concept and demonstration stages and transfer to end users. However, NNSA also supports some activities that can reach into later stages of development, including with foreign partners, and often in collaboration with industry under DOE's Small Business Innovation Research Program. Additionally, NNSA develops space-based nuclear detonation detection sensors and conducts related R&D that contributes to the verification of nuclear treaties. NNSA operates a number of experimental testbeds that support the development and sustainment of core nonproliferation skills and allow researchers to better understand signatures associated with specific processes that a proliferator would need to exercise to develop a nuclear weapon or material. The interagency leverages these testbeds to test operational capabilities in simulated facility environments.

The Intelligence Community (IC) pursues a variety of R&D activities that benefit the nonproliferation and verification mission space. These activities can range from basic R&D to developing fully demonstrated prototypes or technologies. Additionally, through organizations such as the Intelligence Advanced Research Projects Activity and the National Counterproliferation Center, the Office of the

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[3] Characterization includes the measurement, assessment, and modeling of nuclear material and proliferant activities to provide decision makers with actionable information regarding the efforts of a nation or group to develop a nuclear weapons capability.

Director of National Intelligence (ODNI) funds high-risk and high-payoff research programs that have the potential to provide the United States with an overwhelming intelligence advantage and that assist in transitioning innovative capabilities to operators.

The Department of State (DOS), through its Key Verification Assets Fund (V Fund), helps preserve critical verification assets and promotes the development of new technologies that support verification of, and compliance with, existing or potential future arms control, nonproliferation, and disarmament requirements.

The Department of Homeland Security (DHS), through the U.S. Immigration and Customs Enforcement (ICE) Homeland Security Investigations (HSI) Counter-Proliferation Investigations (CPI) program, combats the trafficking and illegal export of the materials, technology, and components that could be used to develop weapons of mass destruction (WMD), including their delivery systems. DHS sponsors R&D to support associated data analytic capabilities.

Additionally, the Department of Defense (DoD) develops and improves technologies that support treaty verification and nuclear explosion monitoring missions. DoD collaborates extensively with DOE and DHS to ensure technology development is cost-efficient and synchronized to support nonproliferation and arms control objectives.
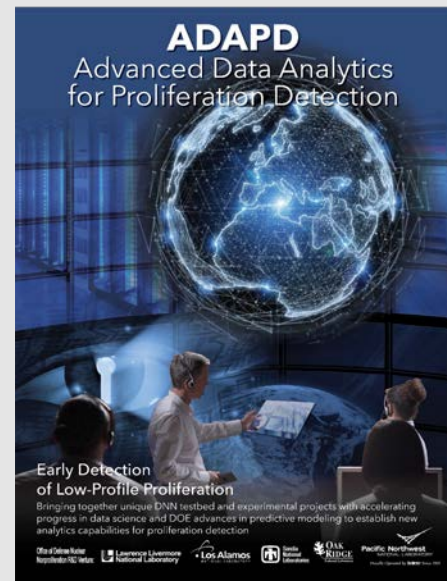
Agencies work together through interagency mechanisms, such as those created under Presidential Policy Directive-33 (PPD-33), Detection and Early Warning of Nuclear Proliferation (August, 2015), to coordinate these multiple efforts across the government in a manner that provides the United States with the capabilities to achieve National nonproliferation and verification objectives. Additionally, agencies coordinate R&D with international organizations, such as the International Atomic Energy Agency, to better account for nuclear and radiological materials and to ensure that those materials are safeguarded. Agencies also collaborate to leverage universities, private industry, and the national laboratories' technical expertise and R&D capabilities to address nuclear nonproliferation and verification challenges.

Developing Predictive capabilities for Nuclear Detection
ADAPD combines direct and indirect data sources in order to develop new predictive capabilities for nuclear proliferation detection with cutting-edge data analytics. ADAPD brings together the best data science practices from industry with the subject matter expertise of the national labs. The project builds on the predictive modeling at experimental testbeds to advance global proliferation detection.

ADAPD
Advanced Data Analytics for Proliferation Detection

Early Detection of Low-Profile Proliferation
Bringing together unique DNN testbed and experimental projects with accelerating progress in data science and DOE advances in predictive modeling to establish new analytics capabilities for proliferation detection

R&D Priorities

In order to advance U.S. capabilities in support of nuclear nonproliferation and verification objectives, Federal agencies should prioritize R&D in the following areas:

Predict, detect, and characterize nuclear proliferation and weapons development activities

Developing a nuclear weapon or device requires specialized capabilities as well as raw nuclear material. Understanding signatures generated by industrial processes needed to produce and weaponize nuclear material is paramount to our ability to detect, characterize, and one day predict nuclear proliferation activities. This includes not only a better understanding of the methods that have historically been used to process nuclear material and construct and test nuclear weapons, but also the development, understanding, and interpretation of alternative methods that have been proposed or developed, such as advanced manufacturing techniques.

1.1 Data analysis methods, data fusion techniques, and predictive modeling for early detection of nuclear proliferation activity. Agencies should work together to identify and collect historical nuclear proliferation data sets, establish a community standard for the minimum acceptable quality of datasets used in the analysis of nuclear proliferation activities, and identify methods most appropriate for curating and sharing those data sets across the government. Research should include new analytical methods to reveal evidence of undeclared materials and activities independent of declared locations. This will require integrating nuclear subject matter expertise from universities, private industry, and the national laboratories into analysis methods that combine novel analytical tools with technical intelligence information to develop new predicative capabilities that improve the U.S. ability to detect proliferation activities. As new data analysis tools and methods are developed, agencies should use established nuclear nonproliferation testbeds and experimental activities to ensure new capabilities can in fact predict, detect, and characterize nuclear proliferation activities and to understand the transferability of these data analysis capabilities across processes associated with nuclear fuel cycle and weaponization activities. [DoD, DHS, DOE/NNSA, IC]

1.2 Capabilities to assess signature generation and emission from activities across nuclear fuel cycle, weaponization, and testing activities, including alternative pathways, in order to develop advanced computational and modeling capabilities. Research should focus on understanding the generation, emission, and propagation of signatures (e.g. chemical, particulate, nuclear, optical, geophysical, and electromagnetic) for highly enriched uranium and weapons grade plutonium production, specifically signatures associated with alternative uranium enrichment methods, fuel fabrication activities, and uranium and plutonium metal production. Work should expand over time to include an understanding of signatures of uranium-233 and neptunium-237 production. Agencies should develop an understanding of signatures indicative of emerging advanced manufacturing techniques that may be used in the development of a nuclear weapon or weapons usable material. Of equal importance, agencies should identify signatures indicative of weaponization and testing, particularly signatures associated with hydrodynamic and hydronuclear testing, high explosives testing, evasively conducted underground nuclear explosions, and low-yield nuclear explosions. NNSA currently operates and is further developing a testbed targeting many of these activities that the interagency can leverage to develop and test capabilities. Where necessary to enable global assessment capabilities, agencies should also work to develop and calibrate region-specific geophysical models and database. [DoD, DOE/NNSA, DOS, IC]

1.3 Technologies that advance proximity and remote sensing capabilities and facilitate persistent monitoring and characterization of special nuclear material production, weaponization and testing, and other proliferation activities. Agencies should develop advanced sensor technologies that lower the limits of detection for both current and new types of field and laboratory analytical capabilities. These efforts should exploit the analysis of multiple signatures (e.g., acoustic energy

and electromagnetic radiation in various spectral regions) where diagnostic information is generated and propagated from source to sensor to improve the ability to detect, locate, identify, and characterize events of interest. Research should also focus on the development of an ability to monitor nuclear reactor operations in proximity to and at remote, or standoff, distances over time. Agencies should target the development of gas collection and sensing technologies that enable continuous monitoring and characterization of nuclear activities at production sites of concern, particularly at standoff distances up to one kilometer. As these new capabilities are developed, testing should leverage existing testbeds to collect and analyze simulated data and establish transferability across different fuel cycle processes. [DoD, DOE/NNSA, IC]

Reduce vulnerability and improve security of nuclear and radioactive materials around the world

The number of nuclear facilities and facilities housing nuclear material continues to rise as countries pursue commercial nuclear energy and increase use of radioactive sources for commercial, research, and medical applications. This increases the risk of theft of nuclear and radioactive materials, equipment, technologies, information, or facilities.

1.4 Alternatives to radioactive and nuclear materials for research, industrial, and medical applications. Agencies should investigate and develop capabilities that would allow the research, industrial, and medical communities to migrate away from using radioactive sources. Agencies should focus on alternatives to radioactive sources, such as cesium-137 and cobalt-60. Agencies should continue to support the conversion of research reactors and medical isotope production facilities from the use of highly-enriched uranium to low-enriched or non-uranium based fuels and production methods. [DOE/NNSA]

1.5 Removal, consolidation, or disposition of weapons-usable nuclear material. Agencies should work to develop innovative capabilities and processes to eliminate outstanding, hard-to-address tranches of weapons-usable materials around the world. [DOE/NNSA]

1.6 Technologies to enhance protection against nuclear material theft and sabotage of nuclear facilities. Agencies should investigate opportunities to use evolving technologies to increase the security of nuclear materials and counter threats from adversaries around the world. [DOE/NNSA]

Provide timely and reliable verification of states' compliance with nuclear safeguards and arms control agreements

International nuclear nonproliferation and arms control agreements include verification measures to provide transparency and demonstrate compliance. Timely and accurate detection of noncompliance allows more effective enforcement of and confidence in international agreements. The United States must improve upon available technological capabilities for efficient and effective verification of existing and potential future agreements.

1.7 Advanced capabilities that improve the ability to detect material diversion or undeclared nuclear fuel cycle activity. Agencies should work to establish a comprehensive understanding of the nuclear data needs of measurement systems used in international safeguards. Advances in data science and machine learning techniques should be explored for their applicability to verifying agreements and providing early warning of nuclear facility misuse. Agencies should develop and improve material accounting measurement techniques and associated technologies that enable the determination of material production quantities over the lifetime of nuclear facilities, in particular for enrichment plant safeguards. For analytical laboratories, research and development of reference materials and standards is needed for quality assurance and qualify control of particle

techniques. Agencies should explore methods to enhance cyber security for unattended safeguards systems. Agencies should also consider research into understanding and addressing the challenges associated with verifying compliance of new facility types and advanced fuel cycle facilities. Researchers should investigate methods for providing continuous monitoring and verification of high value assets, such as spent nuclear fuel and weapons useable material, stored in inaccessible or hard to reach locations. Agencies should also investigate design modifications that can be built into reactor and test facilities from the outset to increase the proliferation resistance of fuel cycle and research capabilities. [DoD, DOE/NNSA, DOS]

1.8 Technologies that improve the ability to monitor and verify nuclear reductions and nuclear infrastructure dismantlement and disablement. Future agreements may require the ability to verify the number of nuclear weapons in a country's arsenal, and to verify dismantlement or disablement of both weapons and infrastructure. Agencies should explore potential methods that would allow inspectors to verify the authenticity of weapons without disclosing sensitive information regarding their design. R&D should leverage advances in data science to assess state-level weapons and material production to provide more accurate analysis, develop new tools in support of negotiations, provide for on-site verification of dismantlement and infrastructure disablement, and support forensic analysis. [DoD, DOE/NNSA, DOS]

Element II: Detection and Attribution

Detection and attribution of nuclear threats contributes an additional layer to U.S. nuclear defense. Effective detection and attribution depends upon strong technical detection capabilities and the ability to connect nuclear information with all other actionable or discriminating information. Research in detection technology must support capabilities deployed in a wide range of operational environments to include foreign ports, border crossings, and in intelligence-directed activities. The ability for the United States to attribute any attack or failed attempt by tracing its intelligence, law enforcement, and nuclear forensics signatures to their source helps to reduce threats.

National policy, as outlined in the National Security Strategy and the Nuclear Posture Review, establishes the following high-level objectives to ensure that the United States can address enduring and emerging challenges in detection and attribution:

- Maintain effective operational capabilities to detect and characterize nuclear materials worldwide
- Determine the origin and provenance of interdicted illicit nuclear or radiological material

Detection and attribution efforts support other elements of America's overall nuclear defense posture. For example, capabilities for direct detection of nuclear materials support nonproliferation and verification efforts. Attribution capabilities help enable effective response to nuclear attack, encourage countries to maintain effective control of their nuclear material, and contribute to deterring adversaries from contemplating covert nuclear attacks or enabling would-be nuclear terrorists or other non-state actors.

Interagency R&D Activities

DoD, DOE/NNSA, and DHS have substantial, well-focused R&D programs that address technical challenges in detection and attribution capabilities. These R&D programs support DoD, DOE/NNSA, and DHS operational programs, as well relevant operational, intelligence, and law enforcement roles of other agencies. Basic and applied research conducted at the DOE/NNSA national laboratories, DoD Service laboratories, in industry, and at academic institutions is supported by DoD, DOE/NNSA, DHS, and ODNI. These agencies coordinate R&D efforts by jointly participating in program reviews, proposal reviews, and research proposal selection in addition to participating in various interagency mechanisms such as PPD-33. This cooperation improves leveraging of program investments, provides opportunities for cross-program collaboration that reduces individual agency funding requirements for larger efforts, and supports the transition of technology from basic research through operationally fielded systems in line with each program's technical requirements. Interagency coordination is particularly important for technical nuclear forensics, in order to preserve a focus on a relatively small and perishable field. The rarity of samples from seized materials or detonations means there is not a strong operational demand signal for technical nuclear forensics capabilities. A consistent, robust, and coordinated R&D effort is therefore necessary to develop and sustain these capabilities, as required by National policy.

The DoD R&D program, conducted primarily by the Defense Threat Reduction Agency (DTRA) Joint Program Executive Office for Chemical, Biological, Radiological, and Nuclear Defense (JPEO-CBRND) and the Defense Advanced Research Projects Agency (DARPA), focuses on nuclear threats outside the continental United States. DoD develops active and passive radiological and nuclear detection technologies in support of military-specific interdiction and rapidly deployable detection, location, and preliminary identification missions. Data correlation and fusion efforts take advantage of multiple intelligence nuclear threat signals, including non-traditional collection modes for nuclear defense such

as imagery and signals intelligence, to provide increased battlefield awareness. In cooperation with NNSA, DoD provides capabilities for post-detonation nuclear forensics. Associated research includes advanced ground/air collection techniques, sensor development, and improved debris characterization and analysis. Senior leader attention is necessary to sustain and improve technical forensics R&D investment; loss of sustained R&D investment can have negative effects on U.S. technical forensics infrastructure and operational capability.

NNSA has a substantial R&D program that focuses on applied research to strengthen U.S. capabilities in nuclear security across the threat spectrum including nonproliferation, counterproliferation, and counterterrorism mission areas. These efforts support nuclear defense and attribution by targeting advancements in the development of materials for improved detection of proliferation activities, tools for improved radiation detection capabilities—including nuclear emergency search, forensic analysis capabilities applicable to interdicted nuclear and radiological material, forensic analysis of the debris and signatures from a nuclear detonation, and advancing the fundamental understanding of nuclear processes relevant to nonproliferation through improved nuclear data. Attribution research at NNSA spans activities in post-detonation nuclear forensics, as well as interdicted nuclear material and device forensics. NNSA also focuses on transitioning technology to commercial partners and other government agencies to meet their mission needs. Additionally, the Intelligence Community sponsors research at DOE national laboratories to meet specific, targeted needs.

On December 21, 2018, the President established the Countering Weapons of Mass Destruction (CWMD) Office within DHS. The CWMD Office was created to elevate and streamline DHS efforts to prevent terrorists and other national security threat actors from using harmful agents, such as chemical, biological, radiological, and nuclear material and devices to harm Americans and U.S. interests. The CWMD Mission is to counter attempts by terrorists or other threat actors to carry out an attack against the United States or its interests using a weapon of mass destruction. CWMD conducts, supports, and coordinates an aggressive R&D program to address significant architectural and technical challenges unresolved by current capability on the near horizon. This includes the development of break-through technologies that will have a clear and demonstrable positive impact on the ability to detect WMD threats. These programs partner with industry, national laboratories, and academia to improve performance while reducing costs and operational burdens of detectors and sensor systems.

Other government agencies also sponsor work to maintain and improve U.S. detection and attribution capabilities. The ODNI collects and disseminates intelligence information concerning radiological, nuclear, and related threats to U.S. security interests. ODNI maintains a focused R&D program for nuclear detection that allows the Intelligence Community to stay abreast of current and future developments in special nuclear material detection, and provides guidance on goals and future needs to support its mission areas. ODNI also supports R&D capability in the attribution framework and all-source fusion of intelligence, technical nuclear forensics signatures, and law enforcement information. Through the Federal Bureau of Investigation, the Department of Justice develops and verifies quality assurance and quality control related to chain of custody of evidence and documented traceability of laboratory analysis methodologies. DOS partners with the interagency R&D community to engage with international partners in order to enhance capability in detection and nuclear forensics, and also secure nuclear material.

R&D Priorities

In order to advance U.S. capabilities in support of nuclear detection and attribution objectives, Federal agencies should prioritize R&D in the following areas:

Maintain effective capabilities to detect and characterize nuclear materials worldwide

Maintaining and improving detection technology serves as an enabling capability in support of U.S. nonproliferation, verification, and counterterrorism missions. The successful direct detection of threat materials, including radiological and/or special nuclear material, depends upon strong technical detection capabilities and connecting that nuclear information with all other actionable or discriminating information. Research in detection technology must support capabilities to detect, locate, and interdict nuclear threats in a wide range of pathways, to include continuous monitoring at foreign and domestic ports and border crossings, wide area search, and in various intelligence-directed activities.

2.1 Improved nuclear detection capabilities through a combination of improved detection materials properties and instrumentation advancement. Agencies should target improved detection capabilities for both neutrons and gamma-rays, particularly for special nuclear material, to include unmanned and autonomous systems capable of searching large areas quickly in remote, urban, and limited access environments. These technologies should be capable of determining direction to source material using networked or non-networked systems with a focus on enabling wide-area search and monitoring and radiation mapping capability development. Work should also investigate tri-mode materials that enable thermal and fast neutron detection plus spectroscopic gamma. Research should also identify new spectroscopic plastic scintillators capable of drop-in replacement in legacy deployed portal monitors. R&D should focus on systems that impose minimal operational burden, reduce non-threat alarms, lower power, lower costs, minimize logistical support requirements, and enable rapid reachback capability to subject matter experts. [DHS, DoD, DOE/NNSA]

2.2 Improved detection of threat materials when shielded, to include both passive and active interrogation methods. Research should focus on development of near-field (distances less than five meters) active interrogation and non-destructive inspection systems that are low dose and capable of rapidly detecting shielded special nuclear material, such as fast neutron imaging and radiography. Agencies should also investigate the possibility of creating portable, high-intensity active neutron and photon interrogation sources. Research should develop or extend current capability to further enhance the detection of heavily shielded threats in pathways where active approaches may not be operationally viable. [DHS, DoD, DOE/NNSA]

2.3 Improved or equivalent detection capabilities with improved size, weight, and power requirements. Agencies should continue to focus on developing detection technologies that reduce cost, size, weight, and power requirements for radiation detection systems while also improving sensitivity and performance. The technology transition of newly-developed detection technologies will enable the development of ultra-compact and low power systems to supplement or replace larger, high power general-use systems. Agencies should explore development and testing of systems that are agile, multi-modal, and capable of supporting a wide range of applications from the laboratory to field operations. This should include technologies that facilitate operational use, law enforcement use, and combat maneuvers; provide real-time situational awareness; and enhance capabilities for command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR). [DHS, DoD, DOE/NNSA]

Sensor Network for Operational Situational Awareness

Improved data fusion and sensor network integration are key to improved operational awareness. Development of enhanced algorithms using artificial intelligence methods will improve detection, localization, tracking, and characterization of nuclear or radiological materials. This is accomplished through an optimized combination of individual sensor-level and network-level processing to combine multi-model data sets into relevant actionable information.
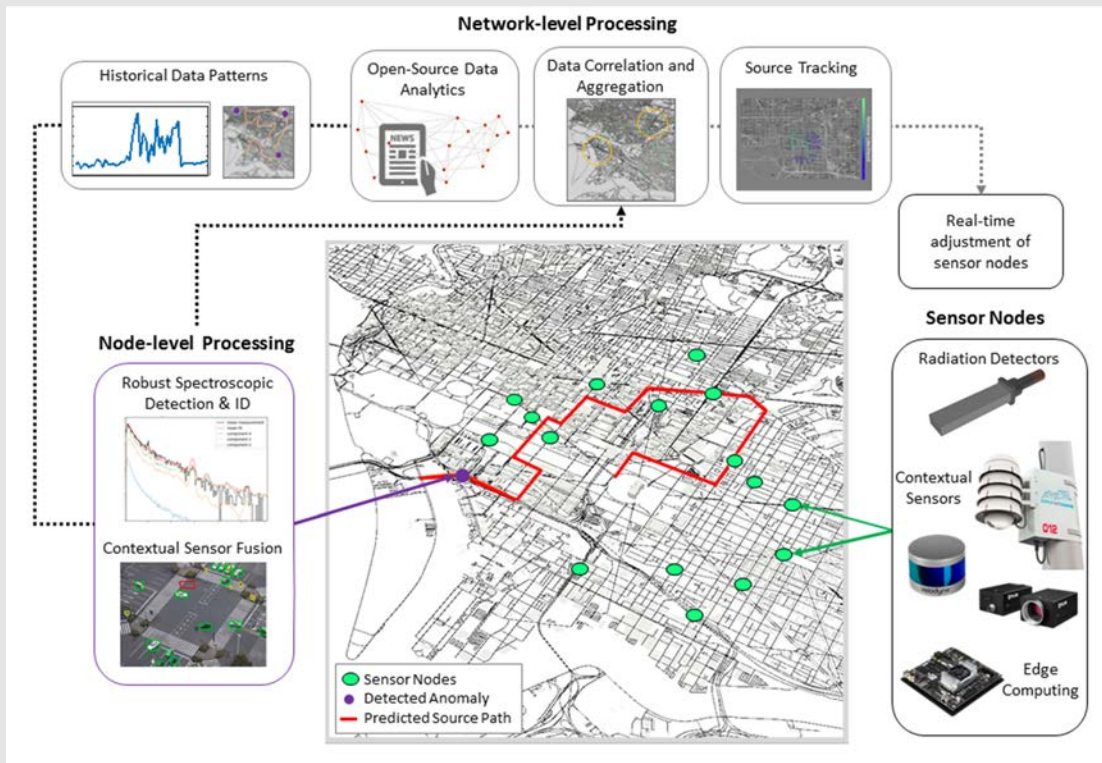
2.4 Data fusion and advanced analysis techniques to harness and exploit disparate data sets through improved sensitivity and effectiveness of direct detection operations. As the number of detection systems increases, agencies will need advanced tools to facilitate data fusion and sensor network integration to best support operational situational awareness and command and control. Agencies should explore development of enhanced algorithms, machine learning, and artificial intelligence methods for enhanced detection, localization or tracking, and characterization of nuclear or radiological materials. Reductions in size, weight, and power requirements of detection systems will require that radiation detection algorithms are fast, robust, and require low computational-burden. Agencies should investigate the ability to deploy algorithms using edge computing to provide on-board, pre-processing, local alerting, and simplified information transmission to a cloud computing infrastructure. With the move to a cloud computing infrastructure, agencies should develop cloud-based data analytics, ranging from graph

analytics to advanced machine learning approaches, which turn integrated radiation and complementary data into relevant actionable information. [DHS, DoD, DOE/NNSA]

2.5 Development of a detection architecture that leverages advances in computing and communications to provide a near real-time common operating picture and alerts for operational users and first responders. Agencies should use advances in computing and communications technology to research and develop a detection architecture that provides a near real time common operating picture and alerts for operational components and first responders. Current DHS and DoD research efforts focus on the development of an information architecture that fuses data from both radiological and non-radiological sensor arrays with existing informational data streams. Analytic algorithms will use these combined data to detect anomalies and provide actionable information in support of operational users. [DHS, DoD, DOE/NNSA]

Determine the origin and provenance of interdicted illicit nuclear or radiological material, interdicted devices, and debris from detonated nuclear devices

Formulating an appropriate response to a nuclear event requires capabilities for attribution to the responsible entity, which could be a nation state, non-state actor, or combination thereof. Through careful analysis of evidence present after the event – i.e. materials after interdiction or debris after detonation – nuclear forensics analyses are central to the attribution process. The nuclear forensics and attribution framework depends upon effective coordination across multiple agencies where each contributes a critical and unique piece of a comprehensive picture. The framework is continually refined through ongoing operational work, exercises, drills, and jointly supported R&D activities. These R&D activities are critical to sustaining and advancing nuclear forensics through traceable scientific methodologies and multi-disciplinary testbed activities that cover a wide range of use cases. These use cases or potential scenarios present key and detailed questions pertaining to the material, design intent, and execution of an interdicted material, device, or post-detonation event. Supporting R&D looks to improve upon the accuracy, precision, timeliness, robustness, and discriminating power of nuclear forensics signatures.

2.6 Advancing nuclear forensics signatures for interdicted nuclear or radioactive materials and devices. Agencies should identify potential nuclear and radioactive material signatures that, using nuclear forensics techniques, can reveal material or device origins. Methodologies should be developed that also reduce uncertainties in the analytical techniques used to characterize interdicted materials and that exploit these signatures with a focus on reducing execution timelines for material characterization. Agencies should explore the development and application of purpose-built, difficult-to-remove isotopic, elemental, or microstructural taggants that when added to materials, facilitate forensics efforts to uniquely identify material origins. Agencies should also leverage their understanding of nuclear and radioactive material signatures to develop and optimize diagnostic methods capable of capturing time-sensitive information from interdicted devices, such as design intent. All of the above provide scientific activity necessary to sustain expertise, facilities, and tools for leading edge nuclear forensics. Senior leader visibility is necessary to re-establish, sustain, and improve technical nuclear forensics. [DHS, DoD, DOE/NNSA]

2.7 Advance development of post-detonation event nuclear forensics signatures. Research should focus on developing timely, robust nuclear blast and fallout debris collection capabilities for a wide range of environments. Agencies should also develop analysis and diagnostic methodologies that improve the U.S. ability to understand debris formation physics and chemistry and the propagation of the debris in a greater range of complex environments. This may require that agencies also

perform research to reduce the uncertainty in nuclear data related to fission and activation products produced within a blast. Research should leverage this improved understanding to advance predictive capabilities for debris propagation and fallout modeling. Agencies should also focus on developing modeling and simulation capabilities that reduce uncertainties in signal propagation from these sensors in complex environments. Work should also expand mapping of debris diagnostic information to the nuclear design space and establish associated uncertainty quantification to improve discrimination capabilities across a range of device types and configurations. The tools, methods, and capabilities developed for this purpose may also benefit a range of nuclear-related missions such as stockpile stewardship, nuclear weapons effects, and consequence management. [DoD, DOE/NNSA]

Element III: Nuclear Deterrence

America's nuclear deterrence policy seeks to convincingly demonstrate to potential adversaries, across the emerging range of threats and contexts, that the United States is able to identify them and hold them accountable for nuclear attacks against the United States, its allies, and partners; and that any nuclear escalation will fail to achieve adversary objectives, and will instead result in unacceptable consequences for the adversary. Effective deterrence of strategic attack ensures that potential adversaries do not miscalculate the perceived benefits of nuclear use. Sustaining a consistent, flexible, and resilient nuclear deterrence posture is critical to America's vital interests, and to broader international stability and security.

The 2017 National Security Strategy makes clear that U.S. nuclear weapons are foundational to U.S. strategy for preserving peace and stability by deterring aggression against the United States, its allies, and partners. It recognizes that U.S. nuclear deterrence strategy cannot prevent all conflict, but makes a key contribution to preventing nuclear attack, non-nuclear strategic attacks, and large-scale conventional aggression.

After 25 years of steadily reducing the number of nuclear weapons and sustaining systems built in the 1980s and earlier, most current U.S. nuclear weapon systems will reach their end-of-service life in the 2025-2035 timeframe. More than 50% of the infrastructure used to design, build, and maintain the U.S. nuclear weapons stockpile is at least 40 years old, with a third dating back to the early Cold War era. The United States does not need to match the nuclear arsenals of other powers weapon for weapon or type by type, but must be able to modernize and build a force that can effectively deter adversaries, assure allies and partners, achieve U.S. objectives if deterrence fails, and hedge against future threats. This requires renewed focus on R&D activities that strengthen U.S. capabilities without mirroring every adversary capability. Renewed R&D is also essential to address limitations imposed by adherence to our nuclear weapons testing moratorium. The United States must focus on developing and acquiring a modern strategic deterrent that will deter adversaries, assure allies and partners, prevent coercion, and hedge effectively against technical, programmatic, operational, and geopolitical uncertainty.

The 2018 Nuclear Posture Review affirms that the fundamental purpose of U.S. nuclear policy and strategy is to deter potential adversaries from nuclear attack of any scale, while also recognizing that deterring nuclear attack is not the only role for U.S. nuclear weapons. The Nuclear Posture Review identifies four critical roles of nuclear weapons in U.S. strategy:

- Deter nuclear and non-nuclear attack
- Assure allies and partners
- Achieve U.S. objectives if deterrence fails
- Hedge against an uncertain future

Nuclear deterrence efforts underpin all elements of America's overall nuclear defense posture, both directly and indirectly. For example, extending U.S. nuclear deterrence to more than 30 allies and partners helps ensure their security, and contributes to U.S. nuclear nonproliferation efforts by reducing incentives for allies to develop their own nuclear capabilities. The ability to detect nuclear proliferation and nuclear materials helps deter adversaries from the illicit pursuit of nuclear weapons. Technical nuclear forensics capabilities and timely, high-confidence attribution contribute to deterring adversaries from contemplating covert nuclear attacks or enabling would-be nuclear terrorists or other non-state actors. Missile defense capabilities contribute to deterrence by helping to convince

adversaries that limited nuclear attacks will not succeed. Finally, resiliency and recovery serve to protect our way of life and also deny adversaries benefit of limited nuclear attack.

Interagency R&D Activities

A number of agencies conduct R&D efforts and programs that support U.S. deterrence policy objectives. A majority of deterrence related R&D is conducted by DoD and DOE/NNSA and coordinated under the Nuclear Weapons Council (NWC), a joint DoD-DOE body responsible under statute for coordinating research on nuclear weapons between those departments. Some basic R&D activities are conducted by other agencies and/or outside the scope of NWC coordination.

NNSA conducts nuclear weapons R&D that supports stockpile stewardship through advanced development of science-based capabilities for maintaining the safety, security, and effectiveness of the U.S. nuclear weapons stockpile without nuclear explosive testing. NNSA also contributes to U.S. warning capabilities by conducting research into space-based sensors and data analysis for the United States Nuclear-detonation Detection System. The Naval Nuclear Propulsion Program conducts R&D to support unique technologies that are critical to delivering improvements in reactor performance and reliability and providing continuous support to the Nation's sea-based strategic deterrent.

Within the DoD, DTRA has a longstanding nuclear technology development effort focused on technologies that support a safe, secure, and effective U.S. nuclear deterrent, including nuclear weapons effects for targeting in support of U.S. strategic deterrence and nuclear survivability standards. DARPA focuses on exploiting high pay-off opportunities to provide revolutionary new system capabilities, which may support deterrence.

The Office of the Secretary of Defense (OSD) supports a wide range of R&D that contributes to deterrence, including R&D related to nuclear weapons security and use control; nuclear weapons stockpile safety, survivability and performance; denying benefits to state adversaries and non-state actors from acquiring, proliferating, or using weapons of mass destruction; and future delivery systems.

The Joint Staff supports R&D in the areas of space, intelligence, deterrence, and operating in a CBRN Environment to inform DoD's understanding of the challenges of the future operating environment. The Services invest in technologies to support current platform development (e.g., the Ground Based Strategic Deterrent, Columbia-class ballistic missile submarine, and Long-Range Standoff Weapon) as well as technology that will enable development of future capabilities. The Joint Staff and OSD encourage the Services to identify those R&D efforts that have the potential for inter-Service impact, for consideration of joint funding.

The Commander of the United States Strategic Command is the Nuclear Command, Control, and Communications (NC3) Enterprise Lead with responsibilities for operations, requirements, and systems engineering and integrations. The Under Secretary of Defense for Acquisition and Sustainment is the NC3 Enterprise Capability Portfolio Manager with increased responsibilities for resources and acquisition. To accelerate the NC3 modernization effort, the NC3 Enterprise continues to maintain and build upon existing synergistic relationships between the R&D and acquisition communities to coherently produce well-aligned R&D and acquisition strategies. These strategies integrate both near and mid-term plans to optimally deliver the right capability to the Services at the right time.

The IC supports R&D to develop new scientific and technical knowledge and to apply such knowledge in developing or improving existing applications for monitoring nuclear capabilities of potential adversaries.

DOS supports R&D for extended deterrence, treaty monitoring and verification, and international cooperation.

R&D Priorities

In order to advance U.S. capabilities in support of nuclear deterrence objectives, Federal agencies should prioritize R&D in the following areas, consistent with the 2018 Nuclear Posture Review:

Deter nuclear and non-nuclear attack; Assure allies and partners; Achieve U.S. objectives if deterrence fails

U.S. strategy calls for applying a tailored approach to effectively deter across a spectrum of adversaries, threats, and contexts. Deterrence succeeds when the adversary is convinced that the costs of aggression outweigh the benefits. The stability and effectiveness of deterrence depends upon adversaries' perceptions, including their perceptions of U.S. military capability, survivability, resilience, political intent, and resolve. Effective deterrence also requires that the United States is seen to possess survivable and credible options for responding to adversary aggression in ways that can plausibly achieve U.S. and allied objectives while protecting U.S., allied, and partner interests. Improved understanding of potential adversaries' decision calculus will facilitate development of a tailored U.S. deterrence strategy, encourage adversary restraint in crisis and conflict, and discourage aggressive and risk-seeking behavior that may lead to crisis and conflict. In order to sustain stable and effective deterrence across a spectrum of adversaries and threats, now and into the future, the United States must sustain and modernize a credible, effective, and responsive nuclear force that provides a flexible set of capabilities and response options. Maintaining a credible, effective, and responsive nuclear force requires sustained investment in the continuous development of technologies that will ensure the flexibility, modularity, and military effectiveness of systems to meet their required design and mission objectives, and be prepared to respond to future uncertainties.

3.1 More effective means to assess deterrence foundations. Agencies should invest in modeling and simulation techniques to improve understanding of how post-Cold War deterrence operates, how to maintain the stability and effectiveness of deterrence strategies tailored to specific potential adversaries, and how to assess that effectiveness. Modeling and simulation should account for multiple conflict domains, escalation dynamics in crisis and conflict, contemporary strategic stability, and reestablishing deterrence after the onset of conflict. Agencies should invest in modeling and simulation techniques to improve the understanding of the future forces that may be required to maintain the stability and effectiveness of deterrence strategies. [DoD, DOE/NNSA, DOS, IC]

3.2 Implementing flexibility in current and future U.S. nuclear force structure. DoD and DOE/NNSA should design flexibility into U.S. nuclear capabilities, in the concept exploration and design phases, to enable modification of future systems at lower cost and with greater speed. Exploration of concepts beyond the preliminary design phase (including prototyping with surrogates for nuclear components) could benefit future systems by shortening development and pre-production phases. These agencies should continue to explore future ballistic and non-ballistic missile warhead requirements based on the threats and vulnerabilities of potential adversaries, and should hedge against the possibility that advances in adversary capabilities could make the U.S. nuclear forces less survivable and effective in the future. Supporting R&D could include modeling and simulation tools to perform mission engineering portfolio management for nuclear deterrent sustainment and modernization. Such tools should be designed to support the U.S. ability to sustain key force attributes—including survivability, the ability to penetrate adversary defenses, the

ability to visibly signal deterrence messages, prompt response to attack, and a range of warhead yield options—in the event of a technological or geopolitical challenge that threatens an element of U.S. nuclear forces. [DoD, DOE/NNSA]

Hedge against an uncertain future

The United States must acquire and maintain the capacity to hedge against an uncertain future. This requires that the United States modernize its nuclear enterprise to ensure the scientific, engineering, and manufacturing capabilities necessary to retain an effective and safe nuclear deterrent force, and to respond in a timely manner to future national security threats, and to technological, operational, and programmatic challenges

3.3 Early identification and remediation of emerging issues. DOE/NNSA should continue to conduct robust nuclear weapons surveillance and experimental programs to identify issues early enough to help prevent technical breakdowns, operational shortfalls, and programmatic challenges. Similarly, DoD should continue a robust weapon system test and evaluation program for early identification of emerging issues. [DoD, DOE/NNSA]

3.4 Advanced nuclear system technology and prototyping capabilities. This should include research into rapid development of nuclear delivery systems, rapid warhead prototyping, alternative basing modes, and capabilities for defeating advanced air and missile defenses. [DoD, DOE/NNSA]

3.5 Capabilities for holding hardened and deeply buried facilities at risk. This should include research into advanced technologies to defeat strategic deep underground facilities, assessment of technological risks and readiness, and specification of required tests to support proof of concepts. [DoD, DOE/NNSA]

3.6 Ensuring the necessary capability, capacity, and responsiveness of the nuclear weapons infrastructure. NNSA should assess which capabilities are currently exercised by life extension programs, stockpile certification, laboratory directed research and development, and technology maturation, to identify any gaps in the full range of the skills needed to design and develop nuclear weapons. DoD and DOE/NNSA should continue to target investments in technologies and programs, such as the Stockpile Responsiveness, Stockpile Services, and Advanced Manufacturing Development programs, that strengthen the U.S. ability to adjust course as necessary in response to emerging challenges, and to reduce the time required for weapon design, development, and initial production. Among these efforts, NNSA should develop options for modifying warheads to increase flexibility and responsiveness, examine the potential for retired warheads and components to augment the future hedge stockpile, and survey past and extant warhead designs to better understand what can be certified without resuming nuclear explosive testing, while rapidly moving toward new production capabilities. [DoD, DOE/NNSA]

Element IV: Missile Defense

Missile defense is an essential component of U.S. national security and defense strategies. It contributes to deterrence of adversary aggression and assurance of allies and partners. Missile defense also strengthens U.S. diplomacy and hedges against future uncertainties and risks. If deterrence fails, U.S. missile defense capabilities limit damage from missile attacks, support military operations, and help preserve freedom of action to meet and defeat regional aggression.

As highlighted in the 2019 Missile Defense Review, today's threat environment is markedly more dangerous than in years past and demands a concerted U.S. effort to improve existing capabilities for both homeland and regional missile defense. This calls for a vigorous R&D program to explore innovative concepts and advanced technologies that have the potential to provide more cost-effective defenses against expanding missile threats.

The current and projected missile threat environment calls for a comprehensive approach to missile defense against rogue state and regional missile threats. This approach integrates offensive and defensive capabilities for deterrence, and includes active defense to intercept missiles in all phases of flight, passive defense to mitigate the effects of missile attack, and capabilities to neutralize offensive missile threats prior to launch, should deterrence fail.

The current Ballistic Missile Defense System (BMDS) provides capability to defend against ballistic missiles with hit-to-kill technology that uses the warhead's kinetic energy to negate the threat. The Missile Defense Review recommends staying ahead of evolving missile threats by investing in technologies, integrating them into a layered defense system, and proving their effectiveness through testing. As adversaries improve their threat systems, the DoD investigates new solutions while improving existing

systems, consistent with U.S. treaty and policy commitments.
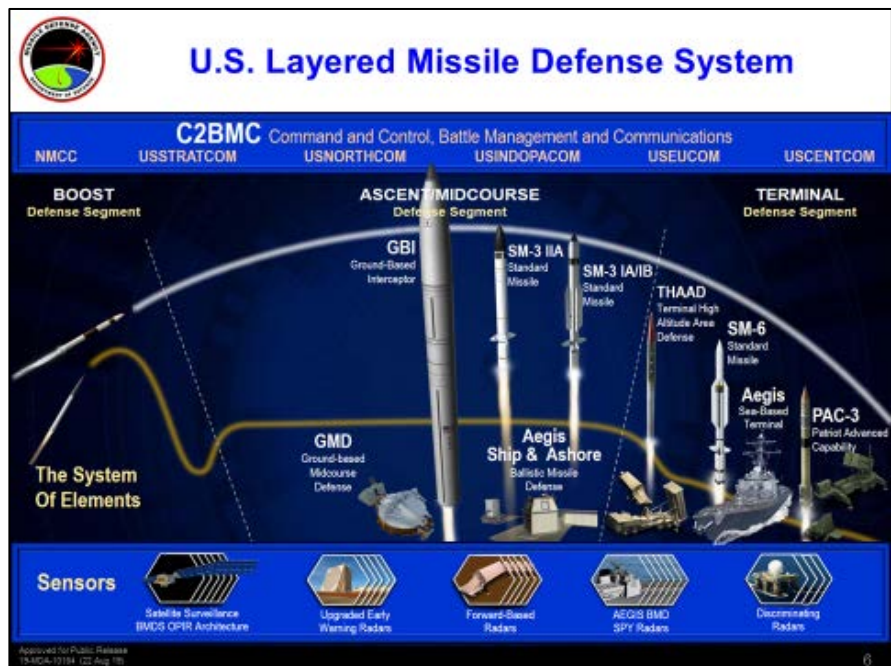
National policy, as outlined in the National Security Strategy and the Missile Defense Review, establishes the following high-level missile defense policy objectives to ensure that the United States can address enduring and emerging missile defense challenges:

- Protect the U.S. homeland, forces abroad, allies, and partners from adversary missile threats
- Continually improve defensive capabilities as needed to stay ahead of missile threats from rogue states
- Hedge against future risks

- Enable Regional and Transregional Military Operations

- Enhance Homeland Missile Defense against North Korea and Iran threats

Missile defense efforts support other elements of the United States' overall nuclear defense posture. For example, missile defense capabilities contribute to deterrence by helping to convince adversaries that limited nuclear attacks will not succeed. Missile defense also contributes to nonproliferation by limiting U.S. vulnerability to rogue nuclear threats and coercion.

Interagency R&D Activities

A number of entities work in concert to develop technologies in support of U.S. missile defense. DoD leverages the expertise of DoD agencies, the military Services, national laboratories, testbeds, industry, and universities to support investments in scientific innovation that advance U.S. technical capabilities.

DoD supports technology risk reduction and technical assessments in multiple areas, including directed energy, space-based tracking, and technology for new kinetic kill vehicles to engage multiple lethal objects with a single interceptor.

The IC pursues R&D activities that benefit missile defense. The IC conducts, leverages, protects, and operationalizes groundbreaking research to create agile and revolutionary IC capabilities. To continue meeting future challenges, the IC must drive new levels of innovation by proactively developing and rapidly incorporating breakthrough and incremental technologies, ideas, and constructs.

To stay ahead of future missile threats, DoD is pursuing R&D of next generation missile defense systems, including space-based sensors, exploration of boost phase defense to intercept missiles earlier in flight, technologies to address advanced cruise missiles and Hypersonic Glide Vehicles (HGVs), and more lethal and cost-effective ground-based interceptors.

R&D Priorities

In order to advance U.S. capabilities in support of missile defense objectives, Federal agencies should prioritize R&D in the following areas:

Protect the U.S. homeland, forces abroad, allies, and partners from adversary missile threats

Missile defense contributes directly to tailored U.S. deterrence strategies for regional and rogue state missile threats to the U.S. homeland. Missile defenses can undermine adversaries' confidence in their ability to achieve political or military objectives through limited missile threats or attacks. An adversary's uncertainty regarding the effectiveness of its attack plans, combined with the prospect of an effective U.S. response to aggression, provides strong incentives for adversary restraint. By shaping an adversary's decision calculus in this way, missile defense diminishes the perceived value of missiles as tools of coercion and aggression. Missile defense also provides additional time and options for U.S. leaders when considering their response to aggression, and thus contributes to the U.S. ability to respond to and stabilize crises or conflicts.

In the event of an actual missile attack, missile defense limits the number of adversary missile warheads that strike their targets, or prevent successful strikes altogether. This is critical to defending the territorial integrity of the United States, saving lives, limiting damage to critical infrastructure, and enabling operational success in regional conflict.

4.1 Left-Through-Right-Integration (LTRI). If deterrence fails and conflict with a rogue state or within a region ensues, U.S. offensive operations supporting missile defense will endeavor to degrade, disrupt, or destroy an adversary's missiles before they are launched. Such operations are part of a

comprehensive missile defense strategy and increase the effectiveness of active missile defenses by reducing the number of adversary missiles to be intercepted. The DoD should continue to invest in capabilities necessary for offensive operations, such as improved attack warning ISR and time-sensitive targeting, as well as the long-range precision and air-, land-, and sea-strike capabilities necessary for destroying mobile missiles prior to their launch. [DoD, IC]

4.2 Flexibility and Adaptability. Flexibility and adaptability in U.S. missile defense development and acquisition programs will enable the United States to tailor its missile defense strategy to help deny potential adversaries any benefit from offensive missile threats or attacks. In support of this priority, DoD is seeking technology that supports development of multi-mission platforms that can support missile defense while also providing other capabilities needed by the Services and IC. [DoD, IC]

Continually improve defensive capabilities as needed to stay ahead of missile threats from rogue states

It is imperative that U.S. missile defense capabilities provide effective, continuing protection against rogue state missile threats to the homeland, now and into the future.

4.3 More cost-effective defenses against expanding missile threats. DoD should continue to invest in new technologies and concepts, and improve and adapt existing weapon systems to field new capabilities rapidly at lower cost. DoD should continue to leverage investments in existing defensive systems and the knowledge gained from prior missile defense research and development to expand U.S. defensive capabilities to new domains, achieve greater integration, and strengthen U.S. capabilities for destroying offensive missiles prior to their launch. [DoD]

4.4 New Concepts and Technologies. Modernization and innovation are critical to ensure the continuing effectiveness of missile defenses. The United States should continue to invest in advanced technologies to meet the increasingly complex threats posed by larger missile inventories and improved countermeasures. Successful science and technology initiatives may lead to operational prototypes that can be evaluated outside the standard acquisition process in order to develop successful technologies more quickly, while also helping to determine as early as possible which efforts would fail. [DoD]

Hedge against future risks

The pace and scale of proliferation and future missile threats is uncertain. U.S. missile defense capabilities and planning must take into account the potential for continuing missile proliferation among potential adversaries, including the proliferation of advanced missile capabilities. Hedging strategies incorporating missile defense help reduce risk and mitigate offensive missile threats that may emerge over time. The U.S. capacity to hedge contributes to deterrence and to the U.S. diplomatic position of strength by helping to reduce potential adversary confidence of a political or military advantage via an expansion or even "breakout" of its missile capabilities.

4.5 Space-based sensors. Space-basing for sensors provides significant advantages. Such sensors take advantage of the large area viewable from space for improved tracking and potential targeting of advanced threats, including HGVs and hypersonic cruise missiles. Space-based sensors can monitor, detect, and track missile launches from locations almost anywhere on the globe, and can provide extremely advantageous "birth-to-death" tracking. Ongoing and planned R&D that supports this priority includes developing ways to collect and process information from existing space-based and terrestrial sensors to track current and emerging HGV threats. [DoD]

4.6 Capabilities for defending against emerging HGV and cruise missile threats. Defense against HGVs is critical to address concerns over the erosion of U.S. regional military advantages expressed in the 2018 NDS. DoD should continue to invest in technology maturation initiatives to enable future evolution against advances in threat capabilities, including HGV and conventional prompt strike threats. DoD is planning to develop, prototype, and demonstrate hypersonic defense component technology, leveraging work done by the Military Services and DoD agencies. [DoD, NORAD]

Enable Regional and Transregional Military Operations

Missile defense supports U.S. and coalition military operations across multiple regions. It helps preserve U.S. freedom of action by limiting adversary capabilities to inhibit or disrupt U.S. regional military operations abroad through missile attacks on U.S. forward deployed forces, allies, or critical in-theater infrastructure. Missile defense is an element of the U.S. capability to counter Anti-Access/Area Denial (A2/AD) strategies that seek to deter or prevent the United States from supporting allies in contested regions. This role for missile defense also provides critical support for the deterrence of attacks and the assurance of allies and partners.

4.7 Tighter Offense-Defense Integration and Interoperability. The United States must maintain the ability to deploy rapidly and sustain its operational plans in an A2/AD environment in which adversaries might seek to use ballistic and cruise missiles for coercion or to overwhelm U.S. forces. DoD should work to define, select, and quickly develop and demonstrate integrated defensive architecture solutions. [DoD]

Enhance Homeland Missile Defense against North Korea and Iran threats

The United States must continue to improve defensive capabilities as needed to stay ahead of North Korean missile threats.

4.8 Boost phase defense. Intercepting offensive missiles in their boost-phase would increase the likelihood of successfully countering missile threats, complicate an adversary's attack calculus by reducing its confidence in its missile attack planning, and reduce the number of midcourse or terminal active defense interceptors needed to destroy the adversary's remaining offensive missiles. Boost phase defense offers the opportunity to engage offensive missiles in their most vulnerable initial boost phase of flight, before they can deploy various countermeasures. Developing kinetic energy intercept technology and systems holds the potential to provide a future boost phase defense capability. [DoD]

Element V: Resilience, Response, and Recovery

In case efforts to prevent nuclear attack do not succeed, America's overall nuclear defense posture must include the ability to respond effectively to and recover from limited nuclear attacks and incidents. Readiness to manage the consequences of a nuclear detonation to save lives, protect critical infrastructure, property, and the environment, and meet the most basic human needs, is part of greater American resilience.

National policy, as outlined in the National Security Strategy and the Nuclear Posture Review, establishes the following high-level nuclear resilience, response, and recovery policy objectives to ensure that America can address enduring and emerging challenges in these areas:

- Protect our critical infrastructure

- Integrate intelligence, law enforcement, and emergency management operations to ensure that frontline defenders have the right information and capabilities to respond to WMD threats

- Respond quickly to meet the needs of the American people in the event of attack on our homeland by improving processes such as risk communication, laboratory analysis, modeling, and health and safety/medical training

- Enhance preparedness to mitigate the effects of nuclear incidents through efforts such as training and exercises

- Respond to nuclear incidents, by managing the consequences of a nuclear detonation to save lives, protect property and the environment, and meet the most basic human needs

Resilience, response, and recovery efforts support other elements of America's overall nuclear defense posture. For example, resilience contributes to nonproliferation by limiting U.S. vulnerability to nuclear threats and coercion.

Interagency R&D Activities

Within DHS, the Federal Emergency Management Agency (FEMA) is responsible for researching, developing, managing, advising, and sustaining the unique capabilities necessary to prepare for, respond to, recover from, or mitigate against the risks of radiological and nuclear incidents. This work includes managing the interagency Nuclear Incident Response Team (NIRT) that supports radiological and nuclear threat, incident, and accident response as well as improving federal, state, local, tribal, and territorial capabilities. DHS sponsors R&D to support radiological and nuclear response and recovery activities. The DHS Science and Technology Directorate (S&T) helps improve community resilience to disasters through technology and tools that support planning, decision making, and mitigation efforts. For example, DHS S&T supports the Canada-U.S. Enhanced Resiliency Experiment to demonstrate that seamless communication between responders.

DOE/NNSA supports resilience, response, and recovery missions as a member of the FEMA NIRT. NNSA sustains and improves the nation's nuclear hazard assessment capability, which provides the capability to rapidly respond to meet the needs of the American people through preparation, technical assessment, interpretation, risk communication, medical advice, and interagency coordination. NNSA prepares for these efforts by developing robust technology and analytical solutions as well as focusing on response capability sustainment. DOE/NNSA's network of labs and sites delivers cutting edge technology and solutions for deployment to Federal government partners.

The DOE/NNSA Offices of Defense Nuclear Nonproliferation and Counterterrorism and Counterproliferation identify, develop, and deliver new solutions for incorporation into response procedures. These solutions leverage coordination with strategic partners, including DHS, DoD, the Environmental Protection Agency (EPA), the Federal Bureau of Investigation, FEMA, the National Aeronautics and Space Administration (NASA), and the Nuclear Regulatory Commission (NRC), to make the unique capabilities of the DOE/NNSA's laboratory network available to support the resilience, response, and recovery mission.

EPA identifies, assesses, conducts, and applies the best available science to address current and future environmental hazards, develop new approaches, and improve the scientific foundation for environmental protection decisions. EPA conducts problem-driven, interdisciplinary research to address specific environmental risks, and is committed to using science and innovation to reduce risks to human health and the environment, based on needs identified by EPA's program and regional offices as well as state, territorial and tribal partners. Over the next five years, EPA will strengthen alignment of its research to support EPA programs, regions, states, and tribes in accomplishing their top human health and environmental protection priorities for improved air quality, clean and safe water, revitalized land, and chemical safety.

The EPA's Office of Research and Development Homeland Security Research Program provides scientific solutions that: (1) improve water utilities' abilities to prepare for and respond to incidents that threaten public health; and (2) advance EPA's capabilities to respond to wide area radiological contamination incidents. This research program strengthens the resiliency of communities by providing water utility managers, on-scene coordinators, laboratory technicians, risk assessors, and emergency responders with the scientific tools, methodologies and technologies, and technical support to prepare for, mitigate, respond to, and rapidly recover from all environmental disasters.

R&D Priorities

In order to advance U.S. capabilities in support of response, recovery, and resilience objectives, Federal agencies should prioritize R&D in the following areas:

Protect our critical infrastructure

In order to protect critical infrastructure, we need to be able to respond quickly with assets and capabilities that can be tailored to different threats in the various critical infrastructure sectors. The protection of critical infrastructure prior to, during, and after nuclear events will directly impact the ability to restore critical services and national capabilities needed for response and long-term recovery efforts. Protection for critical infrastructure in this regard includes the development of threat simulation modeling and other preparatory tools designed to enable better preparedness planning.

5.1 Modeling methods to simulate explosive radiological material dispersal and nuclear detonation and fallout effects in different environments, such as urban, water, or underground environments. Research should focus on the development of methods for coupling urban-scale and regional-scale atmospheric flow and transport models. These models use inherently different modeling methods. Similarly, current nuclear detonation and fallout models are based on empirical data from tests conducted at the former Nevada Test Site (now called the Nevada National Security Site). Future research should expand on this data to develop a capability for developing "first principle" models. To expand on the current atmospheric dispersion modeling present in the community, future research should focus on the development of modeling of threat hazards migrating through bodies of water following a nuclear release. While several agencies have

rudimentary or scenario-specific tools for aqueous or waterborne modeling, they lack models that have tackled the general situation of these migration threats. Finally, research should focus on expanding U.S. institutional capacity for rapidly refining models based on measurement data. Rapid model refinement based on measurements is still an art form that is practiced by only the most experienced of our modelers. Agencies should work to refine existing modeling methods and develop new methods for simulating nuclear explosions and radioactive material dispersion. In addition, agencies should support development of planning and assessment tool for air and water impacts of a nuclear explosion or radioactive material dispersion. [DHS, DoD, DOE/NNSA, EPA]

Integrate intelligence, law enforcement, and emergency management operations to ensure that frontline responders have the right information and capabilities to respond to WMD threats

Prior to, during, and after an event, well-informed responders make better decisions. Enabling responders with effective equipment, methods, and training facilitates high quality and reliable information. This information must then be analyzed and shared in a timely manner with first responders and response organizations for the greatest impact on life saving and recovery operations.

5.2 Interoperable data sharing tools for responders. Agencies should work with partners at Federal, State, and local levels across various sectors including law enforcement, public health, and radiation protection to establish and develop data handling, transfer, analysis, and visualization tools. Improving reach back interoperability between partners is also critical. The FEMA-sponsored common online data management system "CBRN Responder" is currently spearheading a priority effort to create common systems that store and display data. [DHS, DoD, DOE/NNSA, EPA]

Respond quickly to meet the needs of the American people in the event of attack on our homeland by improving processes such as risk communication, laboratory analysis, modeling, and health and safety/medical training

In the event of attack, federal support during response focuses meeting the needs of the American people. The most critical response activity is to provide life-saving and life-protecting medical treatment, and to avoid additional injury by providing health and safety support. Accessible and accurate risk communication from the scientific/responder community to the general public and from the public back to decision-making authorities is crucial to execute emergency plans and actions and to secure responder and public safety. Characterization must be rapid and accurate enough for key decision-making in the areas of risk communication, and to inform real-time response and self-protection guidance. Laboratory analysis and modeling capabilities are critical to adequately assess areas impacted by a radiological event.

5.3 Decision support tools for radiation safety first responders (e.g., turn back limits). In the event of an attack, accessible and accurate techniques and technologies for communicating risk to the general public are crucial to executing emergency plans and actions effectively. Research in this area should include a focus on the development of early protective action messaging—including decision trees—that can be used during an emergency before reliable data are available. This messaging, which should incorporate use of *relative* radiation levels and exposures to facilitate public understanding, will provide the public and responders with actionable information to help save lives and enable response efforts before actionable sampling and measurement data are available to guide local community messaging and response activities. [DHS, DOE/NNSA, EPA, HHS]

5.4 Established baseline of all aerial R/N detection systems' capabilities including a focus on calibration of all systems to enable more rapid response. Research in this area should focus on

developing a process for combining data from multiple aerial systems, including data derived from unmanned aerial vehicle (UAV) platforms and missions. This would allow for more real-time data measurements of ground contamination from specialized airborne assets. As UAV technology continues to advance, research should continue to manage and coordinate the design, development, integration, testing, training, exercising, and operation of wing-mounted radiation detection pods on UAVs. [DHS, DOE/NNSA, EPA]

5.5 Rapid analytical methods. Agencies should work to develop analytical methods and hardware to rapidly determine radionuclides in various media, such as water, soil, sediment, and air sample filters. The goal of this research is to effectively and efficiently measure certain radionuclides that are currently difficult to measure, or for which existing measurement capabilities require extended period of time, and/or have high uncertainties. For example, current analytical measurement and processing techniques for Sr-89 and Sr-90 can require up to 21 days when both are present in the same sample. In addition to the Strontium isotopes, research should also focus on other radionuclides that are difficult to measure without bulky equipment, wet chemistry, or extended periods of time, including some transuranic radionuclides and pure beta emitters such as Pm-147. [DHS, DOE/NNSA, EPA, HHS]

5.6 Improved methods to validate moderate and severe doses to the public and responders. Enhancing our capability to examine individuals exposed to varying levels of radiation supports initial radiological triage to prioritize medical care, recovery operations, and long-term treatment. Research by the biodosimetry community works to expand the range and accuracy of existing methods for detecting the dose received by individuals. In order to continue supporting national preparedness, the Department of Health and Human Services (HHS) is developing techniques for timely biodosimetry for mass casualty nuclear events. Future research should include a focus on developing a timeline for operationalizing one or more techniques for timely biodosimetry during mass casualty events. This timeline should include details such as common calibration methods, image analysis methods, and training of technicians. Further research should also include development and validation of new methodologies that can improve reliability and understanding of long term impacts to patient health. [DHS, DoD, DOE/NNSA, EPA, HHS]

Enhance preparedness to mitigate the effects of nuclear incidents though efforts such as training and exercises

A robust set of training and exercise tools, methods, and capabilities are critical for preparing emergency managers and responders for effective and safe mitigation of impacts stemming from nuclear incidents. Preparedness ensures that communities, responders, and organizations are able to respond and recover when needed most. Such preparedness is critical to maintaining national readiness and creating a standard of resilience for post-nuclear event operations.

5.7 Improved methods to provide training and education on conducting assessments to State, Local, Tribal, and Territorial responders. Agencies should work to develop improved resources, including web-based nuclear incident response training and investigation of new or emerging methodologies (e.g., webinars, remote learning technologies) for group-based training of personnel from across different organizations. Present training R&D activities are multifaceted and include the development and integration of the Radiological Operations Support Specialist into planning and training; the production of scientifically accurate radiological dispersal device animation videos for responders; and the creation of analytical products to help facilitate the transition from earlier to later phases of response. Future research should capitalize on this work

to continue developing alternative training methodologies and online training tools, such as webinars. This will optimize pre-event training and qualifications, as well as just-in-time training. This research must include a focus on the development of just-in-time training for field data collection, in order to provide the ability to quickly increase the number of field data collectors during an event. Additionally, researchers should develop web-based training on the new EPA protective action guidelines for responders and their supervisors. This training should be tested during exercises. Research should also address the need for consolidated, standardized, and quality-controlled training assets and tools targeting radiological/nuclear walk-on responders to improve state and local integration; operational coordination; and technical data collection, assessment, and interpretation. Additional research should focus on developing a programmatic approach to assess readiness to manage the medical consequences of a radiological or nuclear incident in the United States. [DHS, DOE/NNSA, EPA]

Respond to nuclear incidents, by managing the consequences of a nuclear detonation to save lives, protect property and the environment, and meet the most basic human needs

Response operations following a nuclear detonation focus on saving lives, protecting property and the environment, and meeting basic human needs. Strategies, tools, and technologies to conduct remediation in the contaminated area and to manage the resulting radioactive waste are critical elements to successful response and to enable rapid recovery of impacted communities.

5.8 Response and recovery tools and techniques for different types of radionuclides on building materials, environmental surfaces, and critical or sensitive equipment surfaces. Present research in this space will improve the deposition model implemented in various government systems and assessment manuals to make it more consistent with those implemented by other government agencies and regulatory authorities. Similarly, ongoing research is aimed at building faster, more autonomous, and higher fidelity assessments for urban dispersion models and improvised nuclear device hazards. Future research should work to standardize how data about field instruments is stored and integrated across disparate systems. Additionally, there is a need for research into processes for prioritizing sample collection and analysis, systems of networked sensors, and advanced tracking algorithms with data fusion capabilities (e.g. visual plus radiation signature characterization). [DHS, DOE/NNSA, EPA]

5.9 Strategies, tools, technologies, and guidance to perform remediation and waste management operations for both critical infrastructure and surrounding contaminated areas. Research should focus on mitigating the effects of radioactive contamination to water supplies (e.g. drinking water system and wastewater infrastructure). Agencies should prioritize development of capabilities to assess impacts to critical infrastructure, and guidance for the conduct of gross decontamination of critical infrastructure, which includes development and evaluation of decontamination methods and clarification of first responder training and equipment requirements. Agencies should also develop guidance on any alternative approaches that would allow for the protection and use of critical infrastructure. The objective of this research is to develop scientifically sound, effective, and economical methods of decontamination and disposal of contaminated waste. Agencies should also support research to understand the impact of fallout to the water infrastructure system; assess containment methods and strategies for different incident scenarios (radionuclides), including a large-scale incident response; develop of a process to translate cleanup levels to analytical requirements for late phase response and recovery; and develop analytical requirements that match protective action guidelines. [DHS, DOE/NNSA, EPA]

Conclusion

This Nuclear Defense Research and Development Strategic Plan provides a resource to help coordinate Federally-supported nuclear defense R&D, help those involved in this work seek and identify opportunities to advance nuclear defense R&D priorities, and achieve the National nuclear defense policy objectives these priorities serve. Implementing this plan will strengthen America's overall nuclear defense posture, ensuring that we are taking steps today to prepare the Nation to avert or meet the threats of tomorrow.