RESEARCH AND DEVELOPMENT NEEDS FOR IMPROVING RESILIENCE TO ELECTROMAGNETIC PULSES

A Report by the

ELECTROMAGNETIC PULSE RESEARCH AND DEVELOPMENT ASSESSMENT INTERAGENCY WORKING GROUP

SUBCOMMITTEE ON RESILIENCE SCIENCE AND TECHNOLOGY

COMMITTEE ON HOMELAND AND NATIONAL SECURITY

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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About the Electromagnetic Pulse Research and Development Assessment Interagency Working Group

The Electromagnetic Pulse Research and Development Assessment Interagency Working Group (IWG) is organized under the Subcommittee for Resilience Science and Technology, which is part of the NSTC Committee on Homeland and National Security. The IWG seeks to coordinate the activities of executive departments and agencies to improve the resilience of critical infrastructure to the effects of electromagnetic pulses.

About this Document

This document was developed by the Electromagnetic Pulse Research and Development Assessment IWG to address the requirements of Executive Order 13865 entitled *Coordinating National Resilience to Electromagnetic Pulses* (March 26, 2019) regarding Federal research and development needs for improving the resilience of critical infrastructure. This document was reviewed by the Subcommittee on Resilience Science and Technology and the Committee on Homeland and National Security, and was finalized and published by OSTP. This document will be reviewed and updated as appropriate.

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Table of Contents

Abbreviations and Acronyms

DHS	Department of Homeland Security
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOS	Department of State
DOT	Department of Transportation
EMP	electromagnetic pulse
EO	Executive Order
EPA	Environmental Protection Agency
GIC	geomagnetically induced current
GMD	geomagnetic disturbance
M&S	modelling and simulation
NASA	National Aeronautics and Space Administration
NRC	Nuclear Regulatory Commission
NSF	National Science Foundation
NSTC	National Science and Technology Council
OSTP	Office of Science and Technology Policy
R&D	research and development

Executive Summary

Electromagnetic pulse (EMP) refers to a general class of phenomena that produce electric and magnetic fields that can couple to and disrupt or damage electrical equipment and large-scale infrastructure. EMPs can result from naturally occurring space weather or from the detonation of a nuclear explosive device, particularly at high altitudes. Both types of EMP can have large geographic footprints and potentially cause cascading effects across infrastructures, threatening national security and significantly disrupting the economy and everyday life for extended periods of time. Effects from nuclear generated EMP are further compounded by its ability to couple to a wider variety of electronic equipment.

As required by Executive Order 13865, entitled *Coordinating National Resilience to Electromagnetic Pulses* (March 26, 2019), this report presents the first annual assessment of the Federal research and development (R&D) needed to improve EMP resilience of critical infrastructure. This report identifies twelve research needs that span the critical infrastructure sectors and the key areas of knowledge and capabilities needed to develop sufficient resilience measures. These research needs are grouped into the broad research categories of Environment, System Impact, and Remedies.

Environment

- Monitor, analyze, and understand upper atmosphere and radiation belt dynamics during EMP events.
- Improve the accuracy and timeliness of space weather forecasts.
- Measure and compile geomagnetic data and develop tools to improve EMP impact analyses.

System Impact

- Improve models for EMP coupling to infrastructure elements.
- Improve models of national-scale infrastructure.
- Utilize improved models and simulation to better assess the impacts to infrastructure.
- Ensure testbeds have the capabilities to perform fully loaded and connected systems tests.
- Conduct vulnerability assessment testing of representative equipment, systems, and infrastructure.
- Develop and implement instrumentation methods for critical equipment to capture real-time data during geomagnetic disturbances.

Remedies

- Develop methodologies for effective placement of monitoring and protection/mitigation technologies in fielded networked systems.
- Determine and demonstrate viable protection and mitigation technologies and methods.
- Investigate technologies and techniques to improve response and recovery efforts.

Prioritization of these research needs will be determined through the budgeting process and may be informed by interagency discussions.

Aligning research needs to agency missions and responsibilities under the Executive Order serves to highlight potential areas of collaboration and ways to maximize return on taxpayer investment. Coordination with State and local governments, foreign governments and organizations, and with private industry will provide additional opportunities to leverage resources and capabilities.

Introduction

An electromagnetic pulse (EMP) that affects a wide geographic area can be generated from a nuclear detonation, particularly at high altitudes (denoted as HEMP), or by solar activity that induces a geomagnetic disturbance (GMD). [1] Each has the demonstrated capability to disrupt or damage electrical components and systems (such as industrial control systems, large power transformers, network routers, traffic controllers, and radio receivers/transmitters) and large-scale infrastructure (such as the electric power grid, communication networks, satellite networks and interstate pipelines).[2] Both types of EMP can induce effects that range in magnitude and extent depending on the characteristics of the initiating event. Large EMP events (in intensity and area of coverage) can impact regions to continents and potentially cause cascading failures across multiple interdependent types of infrastructure and beyond the initially affected geographical area. Operational capabilities of affected infrastructure could be interrupted for long periods of time causing significant disruption to everyday life and the economy.

The generation of EMP from a high-altitude nuclear detonation is a complex process involving the interaction of nuclear radiation with the atmosphere and distortion of the Earth's magnetic field lines by the rising, heated, and ionized atmospheric layers. These distinct phenomena generate three waveform components (denoted E1, E2, and E3) with differing characteristics.[3] The initial E1 component is very intense and brief with a broad-band power spectrum that couples to both short and long conductors placing a wide variety of electronic systems at risk. The intermediate E2 component has a much lower amplitude but is longer in duration. Its effects are similar to those from nearby lightning strikes. The final E3 component has the lowest amplitude and longest duration. It is a very low frequency field that couples to long-line structures such as long-distance high voltage power lines. Transformers connected to these power lines can be driven into saturation by the induced currents resulting in localized heating, disrupted operations, and potential damage. HEMP events expose electronic equipment and infrastructure to the combined waveform components in rapid succession, potentially greatly compounding the overall effects.

GMDs generate electric fields in a manner similar to E3 but at somewhat lower amplitudes and with potentially much longer duration. Coupling to infrastructure elements and the resulting effects are also similar. A number of large GMD events since the mid-1800s have resulted in interruption of services and damage to infrastructure. Large GMD events will occur in the future; most research suggests there is an approximately 10% probability that the next large event will occur within the next decade. [4]

Large EMP events represent a class of high-consequence disasters that are unique in both geographic coverage and numbers and types of systems potentially debilitated. The President issued Executive

[1] Non-nuclear, man-made EMP devices also exist and may be developed further as weapons; however, these devices have limited range and limited impact in terms of the areal extent of effects.

[2] Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, *Critical National Infrastructures* (April 2008) http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf

[3] Los Alamos National Laboratory, EMP/GMD Phase 0 Report, *A Review of EMP Hazard Environments and Impacts* (Nov. 2016): pp. 13 – 18, LA-UR-16-2830 https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-16-28380

[4] Riley, P. and Love, J. "Extreme Geomagnetic Storms: Probabilistic Forecasts and their Uncertainties," *Space Weather* 15 (2017): pp. 53-64, doi:10.1002/2016SW001470.

Order (EO) 13865, titled *Coordinating National Resilience to Electromagnetic Pulses* (March 26, 2019),[5] to address this threat, in part through coordinated development of technologies, procedures, plans, and operational capabilities to improve EMP resilience of critical infrastructure.[6] As required by the EO, this report identifies the Executive departments' and agencies' (agencies) R&D needs that support the roles and responsibilities outlined in the EO, and support core agency missions. The R&D needs represent a broad interagency R&D program that will be coordinated by the Office of Science and Technology Policy. Agency R&D needs will be assessed on an annual basis to better support the overall requirements of the EO. Initial R&D needs have been influenced by the identification of national critical functions and emergency response planning factors. The program of R&D identified by this report, along with an EMP risk assessment, will inform the subsequent EO activities of infrastructure asset prioritization, test plan and testing capabilities development, and implementation of protections/mitigations through pilot programs.

While there is a substantial body of EMP related knowledge and technical capabilities, there are many key issues still remaining on the path to resilient infrastructures that can only be resolved through coordinated R&D activities. These include improvements in theories, modelling and simulation (M&S) tools, testing capabilities, and operational capabilities as well as generation of additional test results and data. Principal challenges include limited experience and data, the multiple physical phenomena involved in EMP events, the wide range of related spatial and temporal scales, and the complexities of effects within interdependent and networked systems and infrastructure. Infrequent natural occurrence and minimal full-scale testing of these phenomena limit the availability of data and experience to baseline the responses of systems, creating a heavy reliance on M&S to guide decision making. Further, comprehensive M&S of EMP events requires integration of a vast range of physical phenomena including nuclear weapons outputs, space weather, particle scattering, electromagnetic propagation and coupling, and component and infrastructure network response. These phenomena span timescales from sub-nanosecond, for nuclear physics and particle scattering, to minutes, for plasma dynamics and for infrastructure response. Spatial scales range from sub-meter electronics cables in data and control centers, to kilometers-long electrical transmission and long-haul communication lines, to continent-wide electromagnetic fields and infrastructure networks. The potentially wide geographic coverage of EMP events leads also to simultaneous effects on multiple infrastructures, the interconnectivity of which can create complex network responses. This has implications in the development of protections and mitigations, as improvements in one part of the network may complicate overall resilience by increasing risk elsewhere. Models, simulations, tests, procedures, and plans that account for this networked aspect as well as interdependencies across infrastructures are, therefore, of particular importance.

This report discusses an R&D baseline assessment of current EMP-related knowledge and capabilities in eight key areas, identifies gaps and corresponding agency R&D needs, and aligns those needs to agency missions. This approach leads to twelve topical R&D needs that support EO requirements. Alignment identification provides a framework for illuminating potential strategic partnerships that can better leverage resources and improve efficiencies to maximize the benefit of the R&D activities.

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5 https://www.federalregister.gov/documents/2019/03/29/2019-06325/coordinating-national-resilience-to-electromagnetic-pulses

6 Presidential Policy Directive 21 (PPD-21), titled *Critical Infrastructure Security and Resilience*, identifies 16 critical infrastructure sectors that are so vital to the United States that their incapacity or destruction would have a debilitating effect on national security, the economy, public health or safety, or any combination thereof.

Framework for Assessment

Figure 1 captures the breadth of R&D required to improve EMP resilience. The figure shows a progression of broad R&D categories from Environment to System Impact to Remedies. These broad categories are resolved into eight key areas of knowledge and capabilities that are arranged as a linear process flow with each area benefitting from the preceding areas' outputs.

Environment

- **Effect Source Phenomenology**: Understanding the physical processes that generate EMPs. This includes research relating to weapon design and detonation parameters (for HEMP) and charged particle generation and dynamics in the upper atmosphere.
- **Environment Waveforms**: Modeling the spatiotemporal and intensity characteristics of induced electromagnetic fields near critical infrastructure, including influencing factors of the local environment.

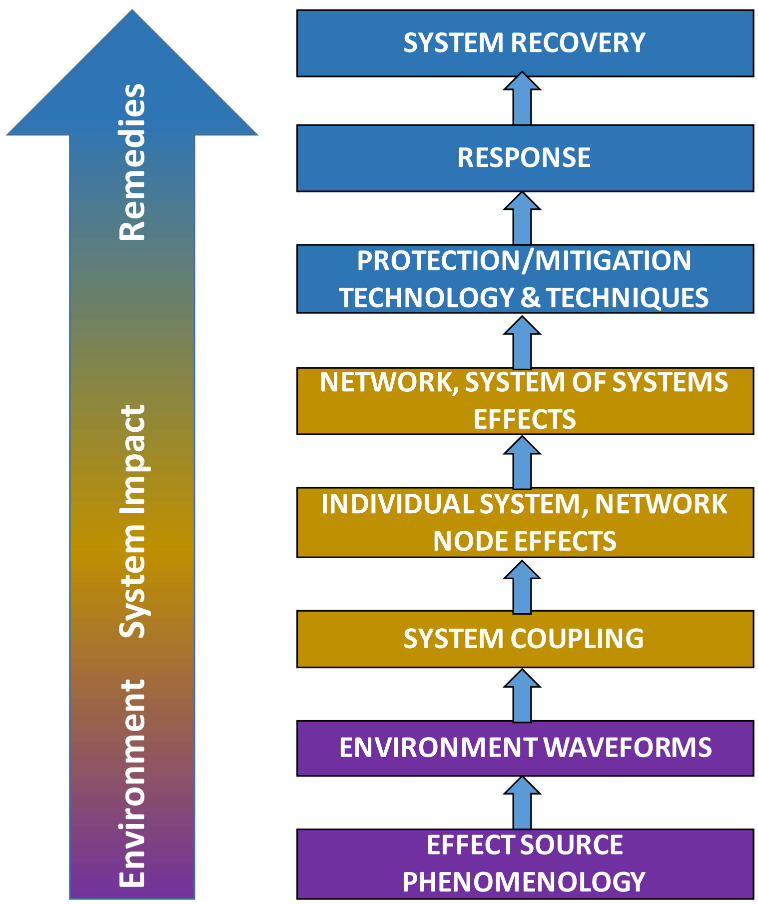

Figure 1. Process flow construct of the principal EMP knowledge areas that enable infrastructure resilience.

System Impact

- **System Coupling**: M&S activities characterizing how electromagnetic fields resulting from EMPs couple to infrastructure elements and induce currents and voltages.
- **Individual System, Network Node Effects:** Modeling and testing of the effects of induced currents and voltages on individual elements of networked infrastructure.
- **Network, System of Systems Effects:** Modeling and testing of the collective response of networked systems to induced currents and voltages, including system interdependencies.

Remedies

- **Protection/Mitigation Technology & Techniques:** Developing and validating technologies and procedures to protect against and mitigate the effects of EMPs on infrastructure.
- **Response:** Determining optimal agency response to an EMP event to minimize adverse effects given an accepted amount of risk.
- **System Recovery:** Developing technologies and methodologies to repair and restore full operational capabilities following an EMP event.

Figure 1 has been utilized to develop a matrix of R&D baselines from agency inputs for HEMP (further resolved into the E1, E2, and E3 components) and GMD, individually. These baselines capture the technical maturity levels of critical operational products (such as tools, data, and capabilities) needed to improve resilience for each of the eight knowledge areas. The classification of technical maturity helps identify key areas where there are gaps in capabilities. These then inform the priority R&D needs that will help fill the gaps through development or improvement of operational products.

The linear flow illustrated in Figure 1 is conceptually useful but does not capture the feedback between knowledge areas that can result in iterative capability advancements. Sufficient knowledge and capabilities exist to enable parallel R&D across knowledge areas; thus, complete understanding in one area is not necessarily required before progress can be made in subsequent areas.

Federal Agency R&D Needs

The twelve identified priority R&D needs support advancements across eight key EMP knowledge areas that contribute to infrastructure resilience. These needs span the R&D lifecycle from basic research to development of operational systems. Federal support throughout the R&D lifecycle is required to ensure national security due to the low probability but high consequence nature of EMP threats.

R&D needs are grouped below into the three broad categories of Environment, System Impact, and Remedies. This organization does not imply a prioritization; individual agencies will determine their respective R&D priorities through normal budgeting processes. Each R&D need is linked to relevant sections in the EO and to the agencies that have related EO or mission responsibilities. The System Impact category has the largest number of identified needs while the Environment and Remedies categories have fewer needs. This is consistent with the natural progression of R&D illustrated in Figure 1 and the current status of the R&D baselines of each knowledge area. R&D activities in the System Impact category should provide the greatest near-term overall benefits including further developing the knowledge and capabilities needed to support greater R&D activities in the Remedies category.

The R&D needs are generally broadly applicable across the various critical infrastructure sectors, due largely to commonality in the types of electronic components used across sectors. The “long line” sectors of Energy, Communications, Transportation, and Water and Wastewater have the majority of directly associated needs because of their susceptibility to both HEMP and GMD. The Energy sector, which includes the electric power grid, has the highest concentration of applicable needs. Beyond its singular importance noted in the EO, the Energy sector is perhaps most susceptible to damaging EMP effects and is essential to the operation and recovery of all other sectors. This further illustrates the importance of considering compounding effects within networked and interdependent infrastructures.

Some R&D needs identified in this report overlap with those identified in the *National Space Weather Strategy and Action Plan*.[7] This overlap emphasizes the importance of those particular research topics for the protection of critical assets and capabilities. However, in an attempt to minimize duplication of effort, this report focusses on topics more directly related to EMP field generation and its effects. It avoids research needs in fundamental solar physics, coronal mass ejections, solar wind, and other similar topics. These topics are important for understanding natural EMP phenomenology, but will be coordinated by the Space Weather, Operations, Research, and Mitigation Interagency Working Group.

Environment

Environment knowledge areas represent foundational scientific knowledge and capabilities that help to inform and advance the subsequent knowledge areas. Additional research in the following topical areas will benefit the overall objectives of the EO, particularly in fully characterizing Earth surface impedance and improving operational capabilities related to GMD forecasting.

Monitor, analyze, and understand upper atmosphere and radiation belt dynamics during EMP events. EMPs can have significant effects on the near-Earth environment, which in turn influences the characteristics of the EMP waveforms that illuminate critical infrastructure. Additional research is needed to more fully understand the coupled magnetosphere-ionosphere-thermosphere system during these large events. This research will involve utilizing both existing and planned ground-based and space-based platforms to continuously capture calibrated observational data that can enable further developments in theory and simulation of the magnetosphere-ionosphere-thermosphere environment. Development and deployment of additional space-based assets can improve the understanding of radiation belt dynamics. Because the largest events are infrequent, studies that aggregate, prepare, and use existing data sets corresponding to extreme events would further aid model development and validation. Where data sets are limited, application of advanced statistical techniques, including machine learning processes, may also improve the confidence of predictions and effects assessments. [EO §§ 5(b)(i), 5(b)(ii), 5(d)(i), and 5(d)(ii); DOC, DOD, NASA, and NSF]

Improve the accuracy and timeliness of space weather forecasts. Accurate, understandable, and timely space weather forecasts enable actions that reduce the vulnerability of critical infrastructure. Government agencies and industry use forecasts to modify electric power grid operations, alter aircraft flight routes, protect astronauts and technology in space, and enable the execution of national security missions.[8] Forecasters use existing computer models to estimate the onset, duration, intensity, and

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[7] Office of Science and Technology Policy, *National Space Weather Strategy and Action Plan* (March 2019) https://www.whitehouse.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf

[8] North American Electric Reliability Corporation, *Effects of Geomagnetic Disturbances on the Bulk Power System* (February 2012) https://www.nerc.com/pa/Stand/Geomagnetic%20Disturbance%20Resources%20DL/NERC_GMD_Report_2012.pdf

affected regions for space weather events; however, improvements are required to meet the needs of the growing space weather community. The Nation must improve existing operational models, identify and transition research models that meet operational needs, and incorporate model outputs into operational forecasts. Key tasks for completing this action include deploying new and innovative observational platforms and techniques, enhancing data integration and utilization, developing metrics to measure and evaluate the performance and capabilities of operational and scientific models, developing and improving models, and identifying computational resource requirements for openly running and testing operational models. A formal research-to-operations and operations-to-research activity will facilitate the transition of new research into operations, enable the improvement and maintenance of existing operational models, and provide feedback to research on improvements needed in modeling capabilities. [EO §§ 5(b)(i), 5(b)(ii), 5(d)(i), and 5(d)(ii); DOC, DOD, and NSF]

Measure and compile geomagnetic data and develop tools to improve EMP impact analyses. A coordinated set of data acquisition and data modeling projects is required to monitor and evaluate natural geomagnetic and related geoelectric hazards. New observatories and variometer stations could be installed and permanently operated at sites across the United States and around the globe to improve the geographic resolution of magnetic monitoring data. Data from these stations could, in turn, directly inform GMD/E3 analyses and time-dependent mapping. Accurate mapping of Earth surface impedance is also needed. This requires completion of the national-scale magnetotelluric survey that has, thus far, covered two-thirds of the continental United States at a grid resolution of 70 kilometers. Higher resolution surveys could be performed in areas where impedance is spatially complicated. Combining an impedance map with GMD/E3 hazard maps enables mapping of geoelectric fields that inform calculations of induced voltages and currents on infrastructure containing long-line elements. These products can enable real-time mitigation of hazardous effects. Finally, retrospective analyses of past GMD events and prospective analyses of possible future events would further inform infrastructure vulnerability analyses. [EO §§ 5(c), 5(d)(i), 5(e), 5(f)(v), and 6(b)(iv); DHS, DOC, DOE, and DOI]

System Impact

Assessments of EMP impact on networked, large-scale infrastructure can only be completed through M&S efforts due to potential cascading effects that may occur from direct testing. However, testing is vital to providing data and baseline responses to benchmark and validate M&S tools for full network assessments. Similarly, use of these tools can inform the types of tests needed, improve testing protocols, and point to potential protections and mitigations. This iterative process results in incremental improvements to both M&S tools and testing capabilities and enhances overall abilities to properly assess vulnerability levels, impact, and risk. Therefore, the priority System Impact topical areas focus on improving M&S tools and expanding testing capabilities with emphasis on addressing the networked aspects of interdependent infrastructures that can lead to cascading effects.

Improve models for EMP coupling to infrastructure elements. Models and simulations provide capabilities for predicting how strongly EMP fields will couple to components and systems. These M&S tools range from high fidelity models of individual components featuring detailed geometries and EMP fields, to lower fidelity models incorporating simplified fields overlaid on approximations of the primary features of systems and facilities or their estimated coupling cross-sections. High fidelity models are computationally intensive but provide the resolution and accuracy to conduct design studies with confidence. Lower fidelity models are less computationally intensive and are more appropriate for modelling large-scale systems but at a potential sacrifice of accuracy and resolution. Research is needed to further develop, improve, and validate high fidelity models and to use those models along with measured data to improve and validate faster-running, lower fidelity models. Initial efforts should be directed towards common elements across infrastructure sectors and for priority systems and infrastructure such as industrial control systems, including supervisory control and data acquisition systems, communication and data center systems, wireless routers, electronic protection and control devices, transportation signaling systems, and electric power transmission and generation systems. Programs should fully leverage existing test data for systems and components. The resulting upgraded and validated models should be integrated into both existing and new simulation tools. [EO §§ 5(b)(iii), 5(e), and 5(f)(v); DHS, DOD, and DOE]

Improve models of national-scale infrastructure. National-scale models of U.S. and allied countries' critical infrastructure enable EMP impact assessments and can determine potential cascading effects of compromised systems and infrastructure over wide geographic areas. These models need to be of sufficient detail and extent to determine the full impact of EMP events on large, interdependent system networks. For instance, current regional and national models of the U.S. electric grid should be expanded to include distribution lines down to at least 69 kV, which will more fully inform hardening requirements for the entire grid. The effects of transient harmonics on loads and transmission networks should also be included. The improved, fast-running coupling models of the previous R&D need should be leveraged along with the measured data generated by the R&D needs below. [EO §§ 5(a)(i), 5(b)(iii), 5(e), and 5(f)(v); DHS, DOD, DOE, and DOS]

Utilize improved models and simulation to better assess the impacts to infrastructure. The upgraded and validated M&S tools should be utilized to conduct more thorough and higher resolution impact assessments. These should include identifying infrastructure elements and sets of elements within the national-scale infrastructure that if disrupted or damaged would cause the most adverse effects to system operations such as transformer substations, water pumping stations, fuel supply terminals and emergency communication repeater sites. Initial efforts should focus on assessing common elements across infrastructure sectors and for priority systems and infrastructure. These activities should be strongly linked to test and measurement activities to ensure adequate feedback for identifying and resolving the critical knowledge gaps that drive uncertainties in the M&S tools. This will help determine additional focus areas for testing and/or hardening, and will help to deliver higher-confidence results in impact assessments. [EO §§ 5(a)(i), 5(b)(iii), 5(e), 5(f)(v), and 6(a)(ii); DHS, DOD, DOE, and DOS]

Ensure testbeds have the capabilities to perform fully loaded and connected systems tests. Expanding testing capabilities will support M&S tool development and improvement, and the development of potential protection and mitigation technologies and techniques. In particular, testbeds are required that are isolated from surrounding commercial infrastructure and are capable of testing large, loaded infrastructure systems (such as electric grid transmission and distribution substation elements, generator stations, data centers, water and wastewater treatment systems, and transportation control systems and related technology) to individual and combined EMP waveforms. Agencies should continue to collaborate to review existing test data, identify gaps in data and testing capabilities, and generate a prioritized list of infrastructure elements to test. These will help inform specifications for the testbeds, which should incorporate sufficient design flexibility to allow modification and expansion to satisfy both present and likely future test requirements. Existing large-scale testbeds may potentially be modified to incorporate the desired enhanced capabilities. Initial efforts should be directed towards developing a testbed for the energy sector that, whether as a new facility or upgraded existing facility, includes all necessary network and control capabilities to accurately reflect grid operations and enable investigation of synergistic effects that can lead to voltage collapse. The testbed should also allow for experiments involving full HEMP and GMD threat level response of large power transformers, the generation and propagation of harmonics, and harmonic impact on equipment and loads as well as development and certification of protections and mitigations. Agencies should further ensure adequate test capacity to support planned testing activities, and should consider portable capabilities for in-situ testing. [EO §§ 5(b)(v), 5(e), 5(f)(v), 6(b)(i), and 6(b)(ii); DHS, DOD, DOE, and EPA]

Conduct vulnerability assessment testing of representative equipment, systems, and infrastructure. Once established, the prioritized list of infrastructure elements should be tested using both existing and enhanced testing capabilities. A well-coordinated testing plan is necessary to account for the wide variety of test items, variations in models, differences in installation configurations, types of tests required, and sufficient testing to develop statistically significant results. The testing plan should leverage existing test data where appropriate, identify the most critical and common items for testing, and prioritize, leverage, and extrapolate data to efficiently cover the broadest and most likely range of potential items, configurations, and scenarios. Networked and connected electric grid infrastructure, including generation, transmission, and distribution systems should be tested as well as other networked systems such as for natural gas and water distribution. Individual items should also be tested including control systems, electronic protection devices, communication devices and systems, commercial vehicles, and common commercial-off-the-shelf electronics such as routers and switches. Tests should be conducted at waveform benchmark levels[9] and up to two times benchmark or failure, whichever occurs first, to better understand how and where degradation and failure occur. Data obtained from this effort will help determine damage thresholds in various configurations, reduce uncertainties in simulation tools, contribute to model validation, and support development of protections and mitigations. [EO §§ 5(b)(iii), 5(e), 5(f)(v), 6(a)(ii), 6(b)(i), 6(b)(ii), and 6(e)(iii); DHS, DOD, DOE, and EPA]

Develop and implement instrumentation methods for critical equipment to capture real-time data during geomagnetic disturbances. Measured data are needed to benchmark and improve models for critical equipment and systems in networked configurations, and to improve M&S assessments of risk to infrastructure. Instrumenting equipment and collecting and analyzing data are therefore vital. The transformers used in the electric grid are of particular concern due to their large numbers, variety of designs, and known susceptibility to geomagnetically induced current (GIC) effects. Instrumentation should be integrated into new transformers of a variety of types and designs to determine where internal hot spots are generated during natural GIC events. Correlation with data from monitors that capture the GIC current entering the transformer will help validate models used to predict thermal behavior. Combining this with real-time magnetic data that indicates GMD event size enables predicting damage and potential failures under different scenarios and aids development of proper mitigations. Data captured from natural events should also be extrapolated to gain insights into E3 system coupling and effects. [EO §§ 5(e) and 6(b)(ii); DHS and DOE]

Remedies

Research in the Remedies category seeks to determine suitable technologies, design characteristics, operational procedures, methodologies, and plans to prevent or limit EMP damage to infrastructure

[9] As directed under Section 6(b)(iii) of the Executive Order on *Coordinating National Resilience to Electromagnetic Pulses*.

and to expedite repairs, as needed, to enable rapid reestablishment of services. As with System Impact, the networked nature of a given infrastructure and its dependence on multiple other types of infrastructure for both normal operational capabilities and for recovery after disaster events significantly complicate the development and implementation of adequate remedies. Accordingly, the priority Remedies topical research areas include these networked, interdependent system effects.

Develop methodologies for effective placement of monitoring and protection/mitigation technologies in fielded networked systems. The interconnectivity of modern infrastructure may lead to complex network effects and responses to EMP events. Hardening or other resilience improvements in one part of a network may increase risk in other parts of the network complicating the achievement of overall infrastructure resilience. For instance, the local blocking of GIC flows in a networked, connected electrical transmission system typically leads to changes in the GICs throughout the entire network and sometimes increases GICs in other susceptible locations. A systems architecture for GIC monitoring needs to be determined and refined for the selection and placement of existing and anticipated monitors and protection/mitigation technologies that are robust over a credible range of field variations and orientations. It should further enable rapid identification of transformers at risk during events and support evaluation of adverse consequences. The cost effectiveness of any particular technology or design method must also be factored into the overall assessment. Equipment and system monitoring technologies and methods are needed that capture data during steady-state operations as well as during and after events to fully characterize and assess effectiveness. Specifications for monitoring, data collection, and data transfer should also be determined before undertaking large-scale demonstration projects. [EO §§ 5(b)(iii), 5(e), 5(f)(v), 6(c)(i), and 6(c)(ii); DHS, DOD, DOE, and EPA]

Determine and demonstrate viable protection and mitigation technologies and methods. Owners and operators of large-scale infrastructure are reluctant to deploy new technologies to improve resilience without sufficient real-world verification testing. Assessments of current protection and mitigation options across infrastructure sectors and across technologies (including cost-benefit analyses and level of verification achieved) will help inform these investment decisions and identify gaps in knowledge and technology areas. Pilot studies are needed to demonstrate and validate the effectiveness and safety of protections and mitigations that are integrated into fielded and networked systems. These studies, tests, and pilot deployments will physically implement the technology, subject it to rigorous operational testing, and document the results, conclusions, and design information needed for owners/operators to assess its effectiveness, robustness, and cost as well as to successfully implement it within their own systems. One option for a pilot study is the design, construction, and validation testing of a new electrical substation with EMP protections. This could demonstrate both the effectiveness of protection/mitigation approaches and the cost estimating methodology. [EO §§ 5(b)(iii), 5(e), 5(f)(v), 5(i), 6(c)(i), 6(c)(ii), and 6(d)(i); DHS, DOD, DOE, EPA, and NASA]

Investigate technologies and techniques to improve response and recovery efforts. Rapid and appropriate EMP response options, such as load shedding on the electric transmission grid or intelligent islanding of grid sectors, may help limit EMP effects and hasten restoration of critical functions. Similarly, optimally sequenced and validated operational procedures and plans can streamline long-term recovery. Research is needed to further examine the outcomes and consequences of possible recovery approaches to identify those that are most effective, and inform the details of resulting procedures and plans. This is particularly important for large-scale events where effects have cascaded to multiple types of interdependent infrastructure requiring proper sequencing of repair and start-up efforts. Methods should account for the complexity of solving for compromised network behavior where critical subsystems have been damaged or rendered ineffective and where data describing the current status of control systems, load availability, or the infrastructure itself is unavailable or incomplete. Development of alternative technologies to supplement or replace damaged or interrupted functionality that is necessary for supporting restoration operations should be investigated. Methods and tools are also needed to assist the analysis and determination of appropriate and cost-effective sparing actions to support long-term recovery. [EO §§ 5(c), 5(f)(ii), 5(f)(iii), 5(f)(v), 5(i), 6(c)(i), 6(e)(ii), and 6(e)(iii); DHS, DOC, DOD, DOE, DOI, EPA, and NASA]

Interagency Coordination and Alignment

Many agencies have responsibilities and conduct planning related to EMP research and preparedness.[10,11] Some agencies have developed a tremendous knowledge base and extensive technical capabilities through decades of R&D activities. Coordinating R&D across agencies will help avoid unnecessary duplication. For R&D needs that have also been identified in the *National Space Weather Strategy and Action Plan*, continued coordination will help ensure that both HEMP and GMD requirements are accounted for, as appropriate, to maximize the impact of R&D investments.

Table I presents the alignment of the identified R&D needs with individual agency core missions and responsibilities as defined under the EO (denoted by filled circles in the table). It further indicates where agencies have shared interests in needs that represent particular topical areas outside of normal mission scope (denoted by open circles). Both responsibility/mission alignment and shared interest present opportunities for leveraging capabilities and knowledge to improve the efficiency of proposed programs. As shown in the table, DHS, DOD, and DOE have the greatest overlap with the identified needs. DHS and DOD are heavily tasked by the EO while DOE has responsibilities for the Energy Sector, which is a prime sector of concern in the EO. NASA and NSF are largely aligned with the Environment needs but NASA also has interests in determining the vulnerability of, and protections for, space assets and supporting ground assets. DHS, DOC, DOD, DOE, and the EPA share interests and responsibilities in developing large-scale testbeds and other testing capabilities. This and the recognized need for a rigorous testing program represent particularly important opportunities for leveraging resources through potential strategic partnerships.

While this report is specifically concerned with reviewing and assessing Federal R&D needs, potential contributions, synergies, and interests of organizations outside the Federal Government can help further the primary goal of improving infrastructure EMP resilience. State, local, Tribal, and Territorial governments have direct control over certain types of infrastructure and generally have interest in the infrastructure that is located within their jurisdictions. Additionally, most U.S. infrastructure is owned or operated by private sector entities that are responsible for complying with relevant standards, regulations, and protocols. Because of this, industry has begun to recognize the need to coordinate with the Federal government regarding EMP resilience.[12] Finally, many foreign governments and

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[10] Department of Energy, *Electromagnetic Pulse Resilience Action Plan* (January 2017) https://www.energy.gov/sites/prod/files/2017/01/f34/DOE%20EMP%20Resilience%20Action%20Plan%20January%202017.pdf

[11] Department of Homeland Security, *Strategy for Protecting and Preparing the Homeland against Threats of Electromagnetic Pulse and Geomagnetic Disturbances* (Oct. 2018) https://www.hsdl.org/?abstract&did=817225

[12] North American Electric Reliability Corporation, *EMP Task Force: Strategic Recommendations* (Nov. 2019) https://www.nerc.com/pa/Stand/EMP%20Task%20Force%20Posting%20DL/NERC_EMP_Task_Force_Report.pdf

organizations are interested in improving their own infrastructure resilience. Coordination on this not only improves the resilience of infrastructure around the world and provides additional avenues of international cooperation but can help ensure U.S. national security activities, broaden the R&D enterprise, and expand the EMP knowledge base at a faster rate. These all represent additional areas of strong mutual interest and offer further opportunities for leveraging outside capabilities and resources to strengthen EMP resilience.

Table I Alignment of R&D Needs to Agency EO Responsibilities/Core Missions and Interests

	Research Need	DHS	DOC	DOD	DOE	DOI	DOS	DOT	EPA	NASA	NRC	NSF
Environment	Monitor, analyze, and understand upper atmosphere and radiation belt dynamics during EMP events (EO §§ 5bi, 5bii, 5di, 5dii)		●	●						●		●
	Improve the accuracy and timeliness of space weather forecasts (EO §§ 5bi, 5bii, 5di, 5dii)		●	●				○		●		●
	Measure and compile geomagnetic data and develop tools to improve EMP impact analyses (EO §§ 5c, 5di, 5e, 5fv, 6biv)	○	●	○	●	●		○				○
System Impact	Improve models for EMP coupling to infrastructure elements (EO §§ 5biii, 5e, 5fv)	●		●	●			○	○			
	Improve models of national-scale infrastructure (EO §§ 5ai, 5biii, 5e, 5fv)	●		●	●		●					
	Utilize improved models and simulation to better assess the impacts to infrastructure (EO §§ 5ai, 5biii, 5e, 5fv, 6aii)	●		●	●		●		○	○		
	Ensure tesbeds have the capabilities to perform fully loaded and connected systems tests (EO §§ 5bv, 5e, 5fv, 6bi, 6bii)	●		●	●			○	●		○	
	Conduct vulnerability assessment testing of representative equipment, systems, and infrastructure (EO §§ 5biii, 5e, 5fv, 6aii, 6bi, 6bii, 6eiii)	●		●	●			○	●	○	○	
	Develop and implement instrumentation methods for critical equipment to capture real-time data during geomagnetic disturbances (EO §§ 5e, 6bii)	●			●	○					○	
Remedies	Develop methodologies for effective placement of monitoring and protection/mitigation technologies in fielded networked systems (EO §§ 5biii, 5e, 5fv, 6ci, 6cii)	●		●	●				●			
	Determine and demonstrate viable protection and mitigation technologies and methods (EO §§ 5biii, 5e, 5fv, 5i, 6ci, 6cii, 6di)	●		●	●			○	●	●	○	
	Investigate technologies and techniques to improve response and recovery efforts (EO §§ 5c, 5fii, 5fiii, 5fv, 5i, 6ci, 6eii, 6eiii)	●	●	●	●	●		○	●	○		

● indicates alignment with EO responsibility/core mission ○ indicates area of interest

Conclusion

Implementing the R&D framework outlined in this report will advance the national priority of critical infrastructure resilience to EMPs in a coordinated, cost-effective, and efficient manner. Federal agencies will continue to assess R&D needs on an annual basis as required by the EO. Future assessments should continue to identify the alignment of new needs to agency missions and interests to help identify areas of mutual interest, facilitate collaboration, avoid duplication, and leverage investments for maximum benefit. Coordination with entities outside of the Federal Government will also be important. State, local, Tribal, and Territorial as well as foreign governments have direct interests in the infrastructure within their jurisdictions. Similarly, the private sector owns or operates the majority of infrastructure and has significant responsibility for implementing resilience plans. Such coordination allows additional opportunities for leveraging resources effectively toward greater national resilience.