Journal of Critical Infrastructure Policy • Volume 3, Number 2 • Fall / Winter 2023

The Electromagnetic Threat to the US: Resilience Strategy Recommendations

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Abstract

This article analyzes the threat of both electromagnetic pulse (EMP) and geomagnetic disturbances (GMD) to various federal agencies and the civilian population of the United States. EMP/GMD events are classified as low-probability/high-impact events that have potential for catastrophic consequences to all levels of government as well as the country's civilian population. By reviewing current literature and conducting two thought experiments, we determined that specific critical infrastructure sectors and modern society are at substantial risk from the effects of these events. Some of the most serious consequences of a large-scale EMP/GMD include long-term power loss to large geographic regions, loss of modern medical services, and severe communication blackouts that could make recovery from these events extremely difficult. In an attempt to counteract and mitigate the risks of EMP/GMD events, resilience engineering concepts prescribe several recommendations that could be utilized by policymakers to mitigate the effects of EMP or GMD. Some of the recommendations include utilizing hardened micro-grid systems, fast tracking available black start options, and various changes to government agency organizations that would provide additional resilience and recovery to American critical infrastructure systems in the post-EMP/GMD environment.

Keywords: Electromagnetic Pulse (EMP), Geomagnetic Disturbance (GMD), Resilience Engineering

Introduction

The purpose of this article is to answer two questions: how ready are the US critical infrastructure systems to withstand the effects of an electromagnetic pulse or

 doi: 10.18278/jcip.3.2.10

geomagnetic disturbance (EMP/GMD), and what actions can be taken in order to increase the resilience of our critical infrastructure systems from such events? Using a thought experiment methodology[1] and incorporating elements of resilience engineering[2], we determined that US critical infrastructure, specifically electric power and telecommunications systems that all other critical infrastructure rely on, is relatively unprepared for a large scale EMP/GMD event. However, we also determined that there are actions that can be taken, some of which are known capabilities that exist, which have the potential to provide additional resilience to various critical infrastructure systems and to provide a level of protection against EMP/GMD events.

To some, EMP/GMD events may seem more like science fiction than reality. There are a multitude of films and books that can seem to sensationalize the effects of EMP/GMD. One book in particular, *One Second After,* provides readers with a frightening reality of what the effects of a large scale EMP attack would be like for everyday Americans as a long-term power blackout caused by an EMP attack cripples a mountain community in rural North Carolina.[3] Books like *One Second After*, while works of fiction, provide exactly the kind of thought process that can allow us to truly understand what the possible second and third order effects could be in a post EMP/GMD environment. How would large geographic areas of the country react to long-term power loss? How would hospitals provide care 96 hours after their backup generators came offline? How would people react when supermarkets are unable to provide food while first responders are either overwhelmed or non-existent? These are the types of scenarios we wanted to understand because they place enormous stress not only on our critical infrastructure systems, but on society as well. The COVID-19 pandemic showcased how low probability/high impact events can have a significant impact on our society as it sent shock waves through our supply chain, financial, and medical sectors. Unfortunately, some studies predict that a large-scale EMP/GMD event would make the COVID-19 pandemic pale in comparison.

Despite the perceived impacts of a large-scale EMP/GMD, there are few studies assessing the capacity for US critical infrastructure to anticipate and respond to such events. This is likely because GMD/EMP events are rare and there is a lack of data on their impacts as well as a lack of imagination for the perceived widespread disaster they could cause. This work is meant to help fill this gap via thought experiments intended to break out a discrete set of critical infrastructure

1 James Robert Brown and Yiftach Fehige, "Thought Experiments," The Stanford Encyclopedia of Philosophy, 2019, https://plato.stanford.edu/archives/win2019/entrieshought-experiment/.

2 John E. Thomas et al., "A Resilience Engineering Approach to Integrating Human and Socio-Technical System Capacities and Processes for National Infrastructure Resilience," *Journal of Homeland Security and Emergency Management* 16, no. 2 (May 27, 2019): 1, https://doi.org/10.1515/jhsem-2017-0019.

3 William Forstchen R., *One Second After*, vol. 1st ed. (New York: Forge, 2019).

impacts.[4] Towards this end, we present two thought experiments, one for an EMP scenario and another for a GMD scenario occurring in the near future. Utilizing data from previous EMP/GMD events as well as from recent natural disasters, these scenarios examine how the US government would respond and what the cascading effects would impact the civilian population. The article then builds on the conclusions from the thought experiments and applies paradigms from resilience engineering to help understand human and technological interactions with EMP/GMD events and provide recommendations to mitigate their impacts. The overall goal is to improve resilience of our critical infrastructure systems.

The remainder of this article is organized as follows: First, an overview is provided on EMP and GMDs are and how they can be detrimental to critical infrastructure systems. It then provides an overview of the EMP and GMD thought experiment methodology and findings and introduces how resilience engineering concepts such as Woods' four concepts of resilience[5] and the Sense, Anticipate, Adapt, and Learn (SAAL) model[6] can suggest strategies to provide both added protection and the ability for systems to rebound against EMP/GMD events. It concludes by offering recommendations to both policymakers and leaders in the private sector for how we can increase the resilience of our critical infrastructure sectors against electromagnetic events.

What are EMP/GMDs and why are they a threat?

An EMP is an electromagnetic wave generated from man-made devices, while a GMD is a naturally occurring solar radiation event that creates similar electromagnetic effects. EMPs can be produced by specialized weapons designed to emit the pulse directly, or as a wave resulting from detonating other weapons like low earth orbit nuclear missiles. In contrast, GMDs occur naturally, such as from coronal mass ejections from the sun. Coronal mass ejections (CMEs) occur when the sun emits a plasma-based emission with an intense magnetic field that can generate an enormous electric current in the Earth's atmosphere.[7] Both EMP and GMD have the potential to cause destructive health and economic impacts as they cause electronic and electrical devices to experience high-energy currents that destroy circuitry and solid-state devices. This means that any device vulnerable to electrical surge, such as computers, cell phones, servers, switchgear, lighting,

4 This work is based on a master's thesis completed by the lead author: Samuel Averitt, "The Electromagnetic Threat To The United States: Recommendations For Consequence Management" (Monterey, CA, Naval Post Graduate School, 2021).

5 "Four Concepts for Resilience and the Implications for the Future of Resilience Engineering," *Reliability Engineering & System Safety* 141 (September 2015): 5, https://doi.org/10.1016/j.ress.2015.03.018.

6 Thomas et al., "A Resilience Engineering Approach to Integrating Human and Socio-Technical System Capacities and Processes for National Infrastructure Resilience," 7.

7 Matthew Weiss and Martin Weiss, "An Assessment of Threats to the American Power Grid," *Energy, Sustainability and Society* 9, no. 1 (2019): 1, https://doi.org/10.1186/s13705-019-0199-y.

transformers, and control systems among many others, can be destroyed by EMP/GMD. Importantly, EMP and GMD can affect large geospatial regions when generated from nuclear weapons or a CME, such that infrastructure systems can be simultaneously destroyed across entire regions and countries.

There are several reasons why even a small-scale EMP or GMD event within the United States would have catastrophic consequences. All 16 U.S. critical infrastructure sectors from healthcare to the defense industrial base have an enormous reliance on the electrical grid, control and supervisory control and data acquisition (SCADA) systems, and internet-based communication which will experience immediate, direct damage from an EMP/GMD. While electric power and telecommunications systems are vulnerable, essentially all critical infrastructure systems can be affected by an EMP/GMD either through direct damage to unprotected electronic components or from cascading failures when power and communications are lost. Whether an EMP/GMD originated from an adversarial attack or from a naturally occurring geomagnetic storm, it is possible that the United States could suffer a severe degradation to its critical infrastructure and potentially experience large numbers of causalities.

EMP Specifics

The effects of EMP events on electrical systems have been well studied during nuclear testing that dates back to the 1960s, first understood by scientists during nuclear testing by the U.S. and Soviet Union in the 1960s.[8] An EMP exhibits three sequential pulses called E1, E2, and E3 that contribute to the disruption or destruction of electronic components and systems. The E1 pulse, referred to as the early time pulse, occurs immediately after a nuclear blast and creates large increases in voltage that can potentially damage standard surge protectors and send tens of volts per meter or millions of volts per kilometer throughout the affected area.[9] The E1 pulse creates conditions for an immediate effect on electrical systems which is caused by high-energy gamma rays that interact with the Earth's atmosphere and creates radiated electromagnetic fields.[10] Because the E1 pulse occurs so quickly and with so much voltage, and because most modern electrical systems lack adequate protection and resilience (e.g., high voltage transformers), many systems cannot withstand the initial phase of an EMP event.[11]

8 See, for example, US House of Representatives, Committee on National Security, Military Research & Development Subcommittee, "Threat Imposed by EMP to US Military Systems and Civil Infrastructure", July 16, 1997.

9 Mao Congguang et al., "Early-Time High-Altitude Electromagnetic Pulse Environment (E1) Simulation with a Bicone-Cage Antenna," *China Communications* 10, no. 7 (2013): 12, https://doi.org/10.1109/CC.2013.6570795.

10 Siva Kumar Pukkalla and B. Subbarao, "Evaluation of Critical Point-of-Entry (POE) Protection Devices for E1 & E2 Pulses as per MIL STD 188-125-1&2," in *2018 15th International Conference on ElectroMagnetic Interference & Compatibility (INCEMIC)* (Bengaluru, India: IEEE, 2018), 1–4, https://doi.org/10.1109/INCEMIC.2018.8704567.

11 Craig R. Lawton, *Sandia's Research in Electric Grid EMP Resilience*, ERPI 2018 EMP Resilient Grid

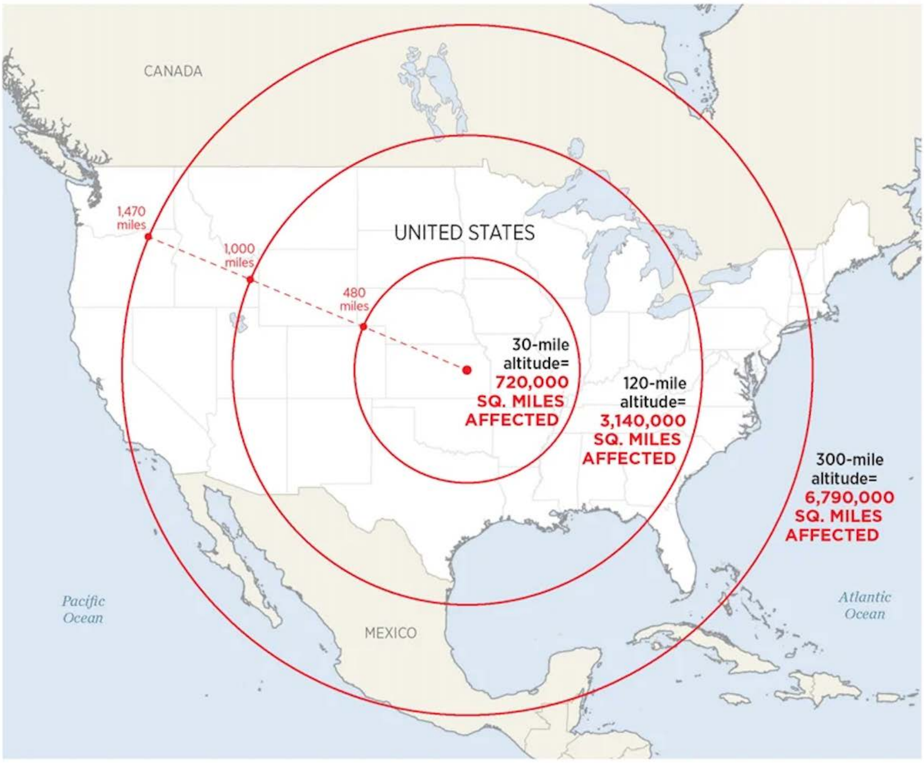

Figure 1: Continental US EMP Burst Map

Source: Threat Posed by Electromagnetic Pulse (EMP) to U.S. Military Systems & Civil Infrastructure, House Committee on National Security, July 16, 1997 from the Heritage Institute

The E2 pulse of an EMP event, referred to as the intermediate pulse, takes place milliseconds after a high altitude nuclear EMP event and immediately follows the E1 pulse.[12] The E2 pulse is comparable in waveform and strength to lightning strikes, which makes it the easiest to protect against as it is a familiar threat to modern society. It does have the potential to put out thousands of volts per kilometer and can cause significant damage to electrical systems, especially when it occurs immediately after the already disabling E1 pulse.[13]

Workshop (Albuquerque, NM: Sandia National Labs, 2018), 14, https://www.osti.gov/servlets/purl/1512391.

12 Soobae Kim and Injoo Jeong, "Vulnerability Assessment of Korean Electric Power Systems to Late-Time (E3) High-Altitude Electromagnetic Pulses," *Energies (Basel)* 12, no. 17 (2019): 1, https://doi.org/10.3390/en12173335.

13 Sirius Bontea, "America's Achilles Heel: Defense Against High-Altitude Electromagnetic Pulse-Policy vs. Practice" (master's thesis, U.S Army Command and General Staff College, 2014), 5, https://www.hsdl.org/?search=&searchfield=&all=America%27s+Achilles+Heel%3A+Defense+Against+High-Altitude+Electromagnetic+Pulse-Policy+vs.+Practice&collection=public&submitted=Search.

The E3 pulse, referred to as the long-term pulse, has significantly different characteristics from the E1 and E2 pulses as it can last seconds to minutes after the EMP event and creates power surges of tens of volts per kilometer.[14] The E3 pulse also differs in that it induces electrical fields which then produce geomagnetically induced currents (GIC)s, which have the same effect that a GMD creates from naturally occurring solar storm events.[15] Power lines can potentially carry the GICs produced from the E3 pulse to massive transformer stations, resulting in significant damage that could cause widespread power outages and greatly impede any recovery of the electrical systems and grids.[16]

Based on the characteristics and effects of the three EMP pulses, high altitude EMP events have the potential to inflict significant damage to modern electrical systems which entire populations rely on for almost every facet of society. Not only can the damage be devastating to electrical systems but depending on the height of burst the effects of the EMP can cover large geographical areas, as the figure 1 depicts.

GMD Specifics

GMD events create disturbances in the Earth's magnetic field due to enhanced solar forces that interact with the space environment that surrounds Earth.[17] A large-scale GMD occurs when a CME forms on the surface of the sun and directs high energy particles towards Earth having the potential to adversely affect GPS systems and satellite communications, and, in extreme cases, to disable power grids on the Earth's surface.[18] The National Oceanic and Atmospheric Administration (NOAA) rates solar events on a scale based on their potential impacts to space and land based systems.[19] Mild radiation events from the sun are classified as S scale events, which degrade satellite communication and high frequency radio transmissions, while a major GMD events are classified as G scale events, which have the potential to create serious impacts to power grids on the Earth's surface.[20] The most powerful G scale GMDs produce GICs that are similar to the effects to the E3 pulse of an EMP and can potentially create the same disabling effects on major power grids. The NOAA's Space and Weather Prediction Center (SWPC) can track and analyze solar activity that may result in a GMD, which can provide between a

14 Kim and Jeong, "Vulnerability Assessment of Korean Electric Power Systems to Late-Time (E3) High-Altitude Electromagnetic Pulses," 2.

15 Kim and Jeong, 2.

16 Kim and Jeong, 2.

17 Department of Homeland Security, *Federal Operating Concept for Impending Space Weather Events*, 2019 Space Operating Concept Report (Washington, D.C: Department of Homeland Security, 2019), 5, https://www.hsdl.org/?abstract&did=.

18 Department of Homeland Security, 6.

19 Department of Homeland Security, 1.

20 Department of Homeland Security, 1.

16–90-hour window of early warning before a GMD event would interact with the Earth's atmosphere.[21]

There have been several instances when GMD events occurred in the past. The earliest recorded GMD event occurred in 1859 and is referred to as the Carrington Event, based on the observations of astronomer Richard Carrington.[22] The Carrington event was observed by several early astronomers at a time when telegraph communication was becoming standard practice of most modern countries.[23] The Carrington GMD had profound and spectacular effects on Earth that included abnormally large Aurora Borealis sightings and destroying over 20,000 km of telegraph lines due to a GIC that overloaded the system.[24] Based on modern analysis and modeling techniques it is estimated that if a GMD as powerful as the Carrington event occurred today, up to 40 million people would be without power for up to two years as GICs will damage wireless communications, control systems, and large electrical transformers that generally take multiple months or years to replace.[25] Failure of these large power transformers would be especially disastrous and cause second- and-third order effects as large scale blackouts impact medical, fuel, transportation, and food production facilities.[26]

More recent events where a CME led to widespread infrastructure failures highlight the need to manage EMP/GMD risks. In 1989, the Canadian Province of Quebec experienced a GMD event that caused a massive blackout that left over five million people without power for a period of nine hours.[27] The same GMD event also had disastrous effects outside of Canada; the storm destroyed a $12-million transformer in the United States, disabled two large transformers in the United Kingdom that had to be repaired, and space agencies temporarily lost communications with hundreds of satellites.[28] Given that power grids in the United States have not been reinforced for modern EMP or GMP threats, and reliance on electrical grids has increased tremendously in the United States since 1989, with data, control, and telecommunications devices now ubiquitous across infrastructure system operations, a similar GMD event today may result in even greater damage to electrical systems.[29]

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21 Department of Homeland Security, 1.

22 Robert Giegengack, "The Carrington Coronal Mass Ejection of 1859," *Proceedings of the American Philosophical Society* 159, no. 4 (December 2015): 421.

23 Giegengack, 421.

24 Giegengack, 423.

25 Weiss and Weiss, "An Assessment of Threats to the American Power Grid," 2.electromagnetic pulse attacks (EMP

26 Mark H. MacAlester and William Murtagh, "Extreme Space Weather Impact: An Emergency Management Perspective," *Space Weather* 12, no. 8 (2014): 535, https://doi.org/10.1002/2014SW001095.

27 Mike Hapgood, "Prepare for the Coming Space Weather Storm," *Nature (London)* 484, no. 7394 (2012): 311–13, https://doi.org/10.1038/484311a.

28 Hapgood, 7.

29 Weiss and Weiss, "An Assessment of Threats to the American Power Grid," 3.electromagnetic pulse

Resilience Engineering Concepts and their Application to EMP/GMD events

Given the widespread recognition that the United States is vulnerable to EMP/GMD, resilience concepts and frameworks can assist policymakers and human operators in creating systems that are designed to survive and recover from stressful environmental events. Resilience is a familiar concept in US national strategy planning. In 2013, the Obama Administration implemented Presidential Policy Directive (PPD) 21 which stated that resilience is a key aspect of protecting national critical infrastructure against both known and unfamiliar threats.[30] The US now prepares for unexpected events using resilience concepts, especially in relation to homeland defense and security of critical infrastructure systems.[31] Resilience goals and practices are commonplace among many federal agencies that would be involved in EMP/GMD response and recovery, including DHS,[32] the Department of Commerce,[33] the DOD, and the DOE[34] among many others.

Despite widespread recognition of need for resilience among US government agencies, large-scale infrastructure failures continue to occur, meaning that systems are not resilient.[35] Alderson suggests that there are at least four barriers inhibiting national resilience to events like EMP/GMD: (1) the interdisciplinary nature of critical infrastructure systems, (2) the overemphasis of predefined threat scenarios, (3) the inability to share information about real systems and needs, and (4) a lack of understanding about resilience itself.[36] Specifically, resilience frame-

attacks (EMP

30 Barack Obama, *Presidential Policy Directive 21: Critical Infrastructure Security and Resilience*, PPD 21 (Washington, D.C: United States. White House Office, 2013), 2, https://www.hsdl.org/?abstract&did=731087.

31 John Moteff, *Critical Infrastructures: Background, Policy, and Implementation*, CRS Report No. RL5809 (Washington, D.C: Congressional Research Service, 2015), 4, https://fas.org/sgp/crs/intel/RL5809.pdf.

32 Department of Homeland Security, *Strategy for Protecting and Preparing the Homeland Against Threats of Electromagnetic Pulse and Geomagnetic Disturbances* (Washington, D.C: Department of Homeland Security, 2018), https://www.hsdl.org/?abstract&did=817225.

33 "National Critical Functions | CISA," National Critical Functions, October 6, 2021, https://www.cisa.gov/national-critical-functions.

34 Department of Energy, *U.S. Department of Energy Electromagnetic Pulse Resilience Action Plan*, EMP Pulse Report 1 (Washington, D.C: Department of Energy, 2017), 20, https://www.hsdl.org/?abstract&did=."plainCitation":"Department of Energy, U.S. Department of Energy Electromagnetic Pulse Resilience Action Plan, EMP Pulse Report 1 (Washington, D.C: Department of Energy, 2017

35 Evan Halper, "A Texas-Size Failure, Followed by a Familiar Texas Response: Blame California," Los Angeles Times, March 18, 2021, https://www.latimes.com/politics/story/2021-03-18/texas-failure-response-blame-california.

36 D.L Alderson, "Overcoming Barriers to Greater Scientific Understanding of Critical Infrastructure Resilience," in *Handbook on Resilience of Socio-Technical Systems* (Northampton, MA: Edward Elgar, 2019), 67–74.

works implemented in many federal agencies overemphasize predefined threats (barrier 2), do not improve our understanding of real systems and data sharing (barrier 3), and do not relate to a large amount of resilience theory and literature (barrier 4). Alderson argues that overcoming these barriers requires drawing upon work in resilience engineering to guide organizational policies and missions.[37]

Two frameworks developed within the resilience engineering technical community for assessing and improving current resilience practices are relevant for EMP/GMD events. First, the resilience engineering literature suggest that government agencies and utility operators can prepare for uncertain events by incorporating the sensing, anticipating, adapting, and learning process (SAAL).[38] The SAAL process describes how technological systems and human cognitive nature interact to maintain a certain level of function during stressful events that are either expected or unexpected.[39] The SAAL process incorporates:

- **Sensing**- "the process to apprehend and interpret information about a system's operations status relative to known and unknown vulnerabilities and system shocks"[40]
- **Anticipating**- "describes the processes involved with imagining, planning, and preparing for possible system changes, emergency events, and crises scenarios relative to present and future conditions of the system, which includes impacts at boundaries"[41]
- **Adapting**- "describes the process governing system responses to both known and unknown changes in stability and operating performance"[42]
- **Learning** -"integrates an open loop cycle of interrelatedness among each subgroup of process (i.e sensing, anticipating, and adapting) to inform and adjust system outcomes while retaining knowledge for future access."[43]

By understanding and implementing the SAAL process, humans can create systems and procedures that are able to quickly respond to new or changing events. The SAAL framework is useful when analyzing how to protect critical infrastructure from both known and unknown events or events which we understand but do not fully grasp the second and third order effects on our systems, such as EMP/GMDs.

37 Alderson, 76.

38 Thomas et al., "A Resilience Engineering Approach to Integrating Human and Socio-Technical System Capacities and Processes for National Infrastructure Resilience," 12.

39 Thomas et al., 6.

40 Thomas et al., 7.

41 Thomas et al., 7.

42 Thomas et al., 7.

43 Thomas et al., 7.

Second, resilience engineering literature suggests that government agencies and utility operators should aim to achieve specific resilience outcomes for infrastructure systems. Woods defines four "concepts of resilience,"[44] that categorize outcomes witnessed when systems survive unexpected stressful events. The four concepts are:

- **Rebound**- how a system can rebound from disrupting or traumatic events and return to normal function
- **Robustness**- the ability of a system to manage increasing stress while still maintaining primary function
- **Extensibility**- how a system can extend or bring additional performance and capacity while experiencing new or challenging events; and,
- **Adaptability**- a system's ability to sustain function while experiencing new or unforeseen events.[45]

Woods' four concepts can assist with the understanding and creation of resilient systems, mainly critical infrastructures, that have the ability to withstand known and unknown events and ensure that systems can continue to operate or successfully rebound after adverse conditions occur. This type of framework is vital for planning how to create electrical systems that could continue to function under EMP/GMD environments.

EMP/GMD Thought Experiments Analyzed through Resilience Paradigms

In an attempt to understand how EMP/GMD events would realistically impact modern day critical infrastructure and society we conducted two thought experiments, one for an EMP event and a second for a GMD event. Thought experiments offer a means to develop realistic, yet fictitious scenarios that reveal decision-making contexts, societal impacts, and other issues relevant for resilience. We developed thought experiments as fictional events that occur in the near future, incorporate present day infrastructure capabilities, and consider known historical societal trends. Then, we analyze each thought experiment via the SAAL and Woods' resilience frameworks to gain a better insight on how government agencies, associated systems, and the civilian population reacted to the stress of EMP/GMD events. Each thought experiment takes into consideration the federal and state level capacities in the pre-event phase, the federal response to the event, the civilian power utility response, the effects on the power grid, and effects on the U.S. population and interdependent infrastructure systems.

44 Woods, "Four Concepts for Resilience and the Implications for the Future of Resilience Engineering," 1.

45 Woods, 1–2.

Thought Experiment 1: Modern Day Carrington Event (GMD)

A GMD the size and strength of the Carrington event occurs in the near future. The oncoming GMD is discovered by the National Oceanographic Atmospheric Administration's Space Weather Prediction Center and determined to impact Earth's atmosphere in 15 hours. Once NOAA confirms the event, the SWPC issues a GMD warning alert to DHS, FEMA, DOD, and all state and local government agencies. The public is notified and elements of the DOE and public utility companies try to prepare the grid for a Carrington class GMD event, while simultaneously all federal and state government agencies execute necessary planning for consequence management and recovery operations. The federal government has no real means to respond due to the 15-hour timetable and is forced to rely on state and local governments' ability to try and mitigate as best as possible. FEMA has time to issue an abbreviated operations order to all of its field offices and state governments but has no real way to react before the 15-hour timeline runs out.

The power utility industry, with the assistance of the DOE, is forced to make significant decisions on how to best prepare the national grid for the impending GMD event. Key critical infrastructure is the main priority of protection as some parts of the national grid would be shut down. Federal, state, and local policymakers provide guidance and direction as to what parts of the country need to be sustained through the GMD event and direct the DOE to immediately disseminate orders and plans to the major power grid interconnections, which include the Western Interconnection, Electric Reliability Council of Texas Interconnection, and Eastern Interconnection who then manage the individual utility operators to prepare the grid for the impending GIC effects. As the GMD event unfolds, large portions of the grid are destroyed and federal agencies are forced to rely on the private utility companies and local governments to provide damage control.

The civilian population is forced to deal with days to weeks of no power, which has disastrous effects on healthcare, emergency response, banking, and other essential services. Both rural and urban areas are devastated by these events as mass migrations occur out of effected areas, which creates additional stress on less affected areas. FEMA attempts to set up areas with key supplies and shelter but due to the rapid timeline of the CME, it cannot deploy enough assets in the time allotted. The civilian population suffers as basic services break down; most community preparedness guidelines only call for 72 hours' worth of essential supplies per family unit, which is nowhere near sufficient in a post-GMD environment.[46] In addition, due to the early warning given to the civilian population, retail and

46 The President's National Infrastructure Advisory Council, *Surviving a Catastrophic Power Outage, How to Strenghen the Capabilities of the Nation*, NIAC-2018-0234 (Washington, D.C: The President's National Infrastructure Advisory Council, 2018), 13, www.cisa.gov%2Fsites%2Fdefault%2Ffiles%2Fpublications%2FNIAC%2520Catastrophic%2520Power%2520Outage%2520Study_FINAL.

grocery stores experience significant supply issues as many people hoard key supplies. Such hoarding behavior was experienced during the COVID-19 pandemic, suggesting that an impending GMD event may could prove to be even worse.[47]

Thought Experiment 2: Adversarial EMP Attack

For the second thought experiment we depicted a hypothetical EMP attack on the United States via a high-altitude nuclear detonation. This thought experiment utilized data from the 1962 Soviet Nuclear EMP tests that were executed in Kazakhstan in which three 300 kiloton warheads were detonated at various altitudes to determine the damage of the EMP effects on Soviet command and control networks.

An EMP attack on the United States occurs in the near future. A hypersonic ballistic missile with a 300-kiloton warhead similar to the weapon used in the 1962 Soviet Nuclear EMP test in Kazakhstan[48] is launched from a submarine in an undisclosed location in the North Atlantic Ocean. The missile is able to evade American missile defense systems, changing its flight trajectory in a rapid and unpredictable manner. The Department of Defense is able to identify and track the missile but has less than 30 minutes before the warhead detonates and has little to no time to notify key domestic agencies such as the Department of Homeland Security. As the missile progresses towards its intended target, the 300-kiloton warhead separates from the re-entry body and detonates 300 km above the Eastern seaboard of the United States. The high-altitude detonation puts thousands of volts per kilometer in the atmosphere with the initial E1 and E2 pulses, destroying most modern electrical systems instantly, including ground-based air defense monitoring stations, while the E3 pulse produces GICs that travel along powerlines and severely damage several transformers, initiating cascading effects to all sectors of critical infrastructure.[49]

Because there was little to no warning to domestic or federal agencies, local governments and communities are forced to deal with the significant effects of the post-EMP environment, which may include widespread power outages, communication blackouts, overwhelmed hospital systems that are without power, and a general state of chaos at all levels of government. Communication failure and the slow dissemination of critical supplies will diminish the abilities of key disaster agencies such as FEMA or state-level National Guard.

47 Janni Leung et al., "Anxiety and Panic Buying Behaviour during COVID-19 Pandemic-A Qualitative Analysis of Toilet Paper Hoarding Contents on Twitter," *International Journal of Environmental Research and Public Health* 18, no. 3 (2021): 1, https://doi.org/10.3390/ijerph18031127.

48 Electric Infrastructure Security Council, "USSR Nuclear EMP Upper Atmosphere Kazakhstan Test 184," Electric Infrastructure Security Council, September 14, 2021, https://www.eiscouncil.org/Library.aspx.

49 Dodge et al., "The Danger of EMP Requires Innovative and Strategic Action," 7.

From a homeland security perspective, there will be a severe degradation in the ability to support local communities, which must depend on their own level of preparedness and ability to maintain order in the most chaotic of circumstances. Depending on the extent of the pulse, there could be serious issues with safely landing aircraft that were airborne during the EMP event and a large number of people who would be stranded at major airports, all of which may be without power. Everyday services such as food production or emergency services may not be available to a large portion of the U.S. population. This is to say, the response from the Department of Homeland Security may be non-existent in the beginning stages of a post-EMP environment.

As there was little to no warning of the EMP attack, the power utility industry will have no means of preparing the grid or taking any mitigating actions against the attack. All three waveforms of the EMP event would be detrimental to the American power grid due to the increased atmospheric voltage and unprepared nature of the grid interconnections. In short, because of the limited reaction time available during a weaponized EMP attack, there would be profound negative impacts to the electrical grid that would, at the very least, cause-long term blackouts in many regions of the U.S.

The effects of a large scale EMP attack on the civilian population have the potential to be disastrous as the level of comfort and services that most American experience in the pre-EMP environment will change dramatically. Many EMP planning documents prescribe that federal and state agencies are responsible for not only providing storage of critical medical and emergency supplies, but also for safeguarding critical infrastructure and creating hardened federal communication networks in order to maintain communications.[50] However, these documents do not consider some of the darker aspects of human nature that may occur when critical services cease to exist, such as desperation from starvation and living in an environment where rule of law may be non-existent, all of which could produce numerous fatalities.[51] In addition, when only 2 percent of the US population currently works in agriculture, and where there is a massive reliance on electric automated services, food security will be a serious concern. Food shortages will occur shortly after the onset of the event, and the ability to mass produce and distribute food will be significantly degraded until power is restored.[52] Much of the emergency distribution of key supplies will be up to state and local jurisdictions and will only be effective if prior planning for EMP/GMD events had occurred—which is doubtful.[53]

50 "EMP Program Status Report | CISA," 29 July 2021, Cybersecurity and Infrastructure Security Agency, accessed July 29, 2021, https://www.cisa.gov/publication/emp-program-status-report.

51 David Stuckenberg, R. James Woolsey, and Douglas DeMaio, *Electromagnetic Defense Task Force 2.0: 2019 Report*, LeMay Paper No. 4 (Maxwell Air Force Base, Alabama: Air University (U.S.). Press Curtis E. LeMay Center for Doctrine Development and Education, 2019), 109, https://www.hsdl.org/?abstract&did=828407.

52 Stuckenberg, Woolsey, and DeMaio, 109.

53 George H. Baker, "Electromagnetic Pulse Resilience of United States Critical Infrastructure: Prog-

As mass blackouts and absences in critical services continue to exist as a result of the EMP attack, the civilian population will be subjected to conditions that have not been experienced since the advent of the industrial age. Much of the population will be exposed to both extreme heat and cold temperatures as HVAC and air conditioning systems will be unable to function. Wastewater and sewage system failures will produce unsanitary conditions in the areas that are within the EMP blast radius and will make many areas uninhabitable for the civilian population as clean water will be harder to acquire as blackouts continue.[54] Life as most Americans know it will be changed for a very long time. The length of recovery time from a weaponized EMP attack is hard to predict, but some sources estimate recovery will last months to years as some vital electronic assets such as transformers can take many months to construct under normal conditions.[55]

Analysis of the Thought Experiments and Potential Recommendations for Mitigation

A GMD/EMP event, while rare, has great potential to inflict significant damage to our critical infrastructure systems and send cascading effects that could impact every American citizen. Having strategies to deal with post-GMD/EMP environments will not only save lives, but are necessary for America to remain secure if such an event ever occurs. Towards this end, we analyze each thought experiment via the SAAL framework and Wood's Resilience Concepts. Specifically, the SAAL framework reveals how various actors perceived the events in and the Woods' concepts inform pre- and post-event recommendations.

Overall, both thought experiments showcased that in case of a GMD or EMP event, the ability of the federal government will be severely degraded and most of the consequence management will be left to state and local agencies. In other words, the ability for various agencies to sense what is occurring was almost nonexistent in the post-event environment. It is also apparent that the ability of the civilian population to deal with these events is entirely dependent on the amount of preparation that is done at the family or household level. In both events, communities will respond based on how well they can initially operate without federal assistance. Hence, where appropriate, analyses and recommendations are provided separately federal and utility providers and civilian populations.

ress and Prognostics," *Journal of Critical Infrastructure Policy* 2, no. Spring/Summer 2021 (200AD): 38.

54 John Foster Jr. et al., *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack: Critical National Infrastructures* (McLean, VA: Electromagnetic Pulse Commission, 2008), 10, https://apps.dtic.mil/sti/citations/ADA484672.

55 Foster Jr. et al., 6.

SAAL Framework

Utilizing the SAAL framework, we created approximate timelines for both events that showcase how federal agencies and the civilian population reacted.

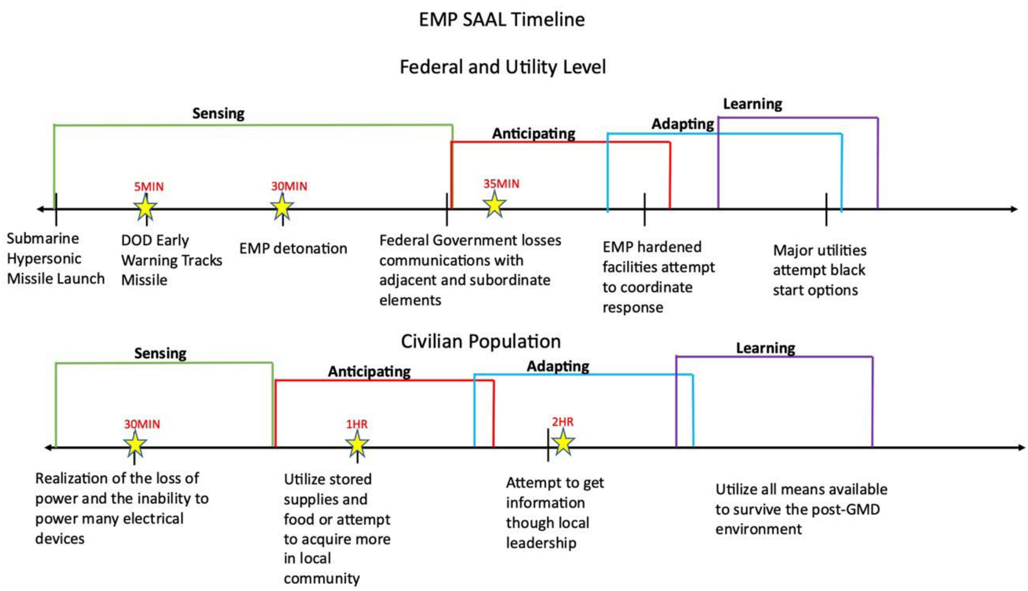

Figure 2: EMP SAAL Timeline

As seen in Figure 2, both thought experiments are broken down by each phase of the SAAL methodology for federal agencies and the civilian population. Key times are plotted on the charts to denote how much time various entities had to understand how these events were unfolding and what actions could realistically be taken. The GMD event demonstrated that NOAA was able to provide some level of reaction time to allow a limited amount of early warning to various levels of government and the civilian population whereas the EMP event had little to no reaction time, which had profound effects on both government agencies and the civilian population.

Based on the timelines created from the thought experiments, we propose a far greater level of preparedness at the jurisdiction level, better lines of communication between the DOD and domestic agencies for pre-event EMP awareness, and the incorporation of adaptable technology, such as hardened microgrids and black start options, that can provide electric power in a post-EMP/GMD environment. From a federal government perspective, the implementation of some of these recommendations may be difficult as many recent events have taken priority such as domestic terrorism, the response to COVID-19, and a return of great power competition. However, it can be argued that the basic tenets of preparedness and a sustainable, resilient grid system are extremely important in any disaster or contingency. In addition, steps should be taken in order to ensure the DOD can quickly disseminate information on adversarial EMP attacks to domestic agencies such as DHS and NOAA to ensure contingency planning can be at least initiated before large parts of the country lose power and the ability to communicate.

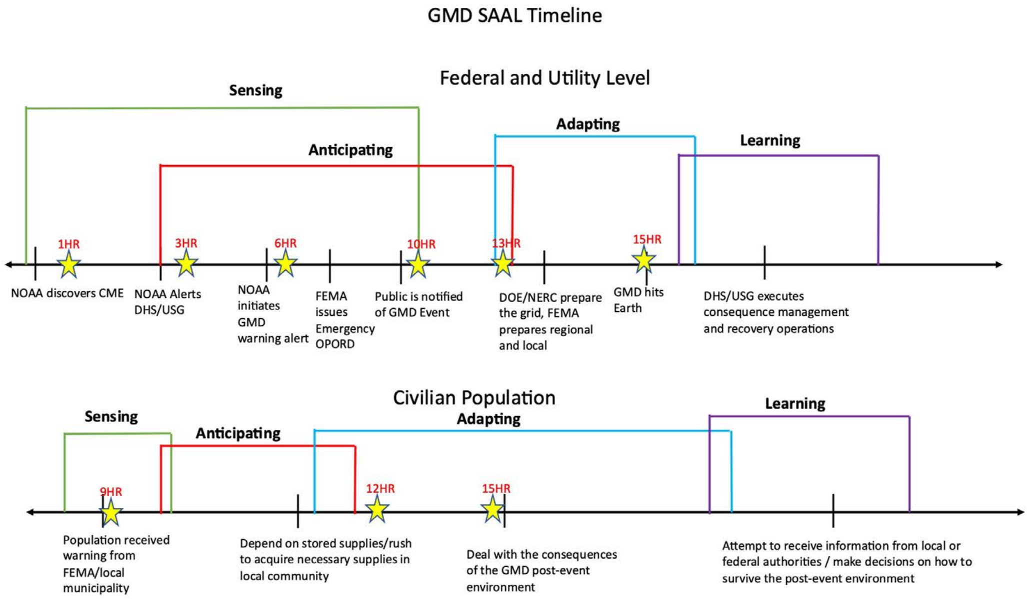

Figure 3: GMD SAAL Timeline

Woods' Resilience Concepts

Where Woods' concepts of resilience focus on outcomes, analyzing the thought experiments through this framework provides recommendations for protection and mitigation to EMP/GMD events. The pre-event recommendation is the development of hardened microgrid infrastructure that focus on robustness and sustained adaptability. The post-event recommendation involves black start recovery options that focus on rebound and graceful extensibility.

Hardened microgrids have the ability to operate off of the national grid but can also function in stand-alone island mode in order to support key infrastructure operations during an EMP/GMD event utilizing the concepts of robustness and sustained adaptability. Various microgrid systems, hardened to the MIL-STD-188-125-1 standard, provide policy makers and utility operators additional flexibility and resilience to maintain power to large geographic areas even when the electrical grid is disabled during an EMP/GMD event. Microgrids are a key strategy to mitigate the cascading and interconnected nature of both critical infrastructure systems and modern society by providing a means for communities or customers to "come off" the grid and sustain power through adverse conditions.

Modern microgrids are being constructed for three main purposes throughout the world; energy security, economic benefits, and clean energy.[56] However, the main reason for microgrid investment in the United States is added resilience and reliability of the electrical grid.[57] In an EMP/GMD scenario, massive regional power outages are to be expected which have serious implications to both other critical systems and the civilian population. However, hardened microgrid systems, capable of operating from battery or renewable energy sources independent of the national grid, helps to safeguard systems in withstanding stressful events, adapt to new circumstances, and extend their intended purpose to provide added resilience.In addition to these advantages, microgrid concepts could potentially mitigate the ever-present vulnerability of powerlines being destroyed by natural disasters by having the ability to operate without being dependent on regional or local utilities.[58]

Microgrid systems are not without challenges or controversy as these systems have specific issues that need to be addressed in order for regional or national solutions to be achieved. Microgrids are considered a grey area when it comes to legal and regulatory oversight as private citizens could make microgrids that are potentially incompatible with national grid system integration.[59] It is unknown if microgrids would be regulated by state or federal regulatory oversight as some systems could be operated or installed in an unsafe manner by commercial companies or individuals. To be most effective, microgrids need to be produced and regulated by national standards as the interconnection to the national grid could be problematic if regulations were not strictly enforced.[60] Regional interconnection utilities and federal laws would need to determine who could operate a microgrid and set specific standards as to how and when they can disconnect from the national grid and operate in island mode. It is also unrealistic for every single microgrid system to be hardened to the MIL-STD-188-125-1 standard as it is expensive and resource intensive. However, key strategic microgrid hubs that sustain critical infrastructure systems or large populations could be sufficiently hardened in order to provide resilience during EMP/GMD events.

Black start recovery options include a large system of interconnected units that can potentially re-energize the grid if a widespread power outage occurs in the United States.[61] These options are designed to respond to black sky events, which

56 Adam Hirsch, Yael Parag, and Josep Guerrero, "Microgrids: A Review of Technologies, Key Drivers, and Outstanding Issues," *Renewable & Sustainable Energy Reviews* 90 (2018): 404, https://doi.org/10.1016/j.rser.2018.03.040.

57 Hirsch, Parag, and Guerrero, 404.

58 Mishra et al., "Microgrid Resilience," 3.

59 Hirsch, Parag, and Guerrero, "Microgrids," 407.

60 Hirsch, Parag, and Guerrero, 409.

61 Sherrell R. Greene, "Nuclear Power: Black Sky Liability or Black Sky Asset?," *International Journal of Nuclear Security* 2, no. 3 (December 1, 2016): 9, https://doi.org/10.7290/V78913SR.

are defined as "outages that would span very large regions, and utilities could require weeks or months to restore power to even the highest priority customers."[62] Black start options are powered by "Black Start Units that are power generation assets that can be used independent of the national grid such as hydroelectric dams, gas turbines, or oil fired units."[63] Various black start units are coupled and wired to strategically located load centers that power local "islands" throughout the grid and can be choreographed to power larger parts and eventually bring the national grid back online.[64] Currently, most power production facilities, including nuclear reactors, are not constructed to withstand the effects of EMP/GMD events.[65] In order to utilize black start options for EMP/GMD events, the units need to be sufficiently hardened in order provide a reliable source of power. To provide adequate protection and shielding against EMP/GMD events, the U.S. military standard of MIL-STD-188-125-1 would need to be utilized. This standard requires that key facilities extensively test and provide shielding of 80 on an attenuation scale that amounts to 80mm of concrete or steel protection that includes specialized doors, grounding procedures, and enough backup power for up to 30 days of operation.[66] While the cost of hardening these facilities would have huge economic and financial requirements, such measures would ensure that the electrical grid could provide a source of rebound and extensibility for EMP/GMD events.

While there are numerous ways to initiate black start options to include fossil fuel locations such as gas turbine plants, hydroelectric dams may be the best option in a post EMP/GMD environment as the ability to produce power and water will remain intact as long as the facility is hardened as per MIL-STD-188-125-1.[67] Hydroelectric dams are generally thought of as among the Department of Energy's most reliable black start options as there is usually always enough water to activate the turbines to begin black start operations and hydroelectric dams require minimal amounts of power to operate as cooling and fuel storage is not required.[68] As

62 Greene, 5.

63 Greene, 9.

64 Mishra et al., "Microgrid Resilience," 2.

65 James Conca, "Can Nuclear Power Plants Resist Attacks Of Electromagnetic Pulse (EMP)?," Forbes, accessed November 1, 2021, https://www.forbes.com/sites/jamesconca/2019/01/03/can-nuclear-power-plants-resist-attacks-of-electromagnetic-pulse-emp/.

66 National Cybersecurity and Communications Integration Center, "Electromagnetic Pulse (EMP) Protection and Resilience Guidelines for Critical Infrastructure and Equipment," Version 2.2 – 5 February 2019 (Arlington, Virginia: National Coordinating Center for Communications, February 5, 2019), 1, chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=https%3A%2F%2Fwww.cisa.gov%2Fsites%2Fdefault%2Ffiles%2Fpublications%2F19_0307_CISA_EMP-Protection-Resilience-Guidelines.pdf&clen=7010467&chunk=true.

67 Jose R. Garcia et al., *Hydropower Plants as Black Start Resources*, ORNL/SPR2018/1077 (Oak Ridge National Labs, TN: Department of Energy, 2019), iii, https://www.energy.gov/sites/prod/files/2019/05/f62/Hydro-Black-Start_May2019.pdf.

68 Garcia et al., iv.

long as these assets are protected from the effects of EMP/GMD events, they can serve as reliable assets for getting the national grid back online.

A second, and more risky, black start option is using nuclear reactors which typically have up to a year of fuel, which surpasses most fossil fuel reserves.[69] There are a variety of dangers that occur when nuclear power plants are forced to come off the national grid after an EMP/GMD event, including nuclear meltdowns. However, various contingencies such as robust back-up power supply systems and extensive damage mitigation guidelines, developed with decades of experience from the nuclear industry and Nuclear Regulatory Council, provide some safeguards.[70] This, along with hardening techniques, could make nuclear power plants a robust black start option. Nuclear power plants in the United States are required to comply with the Nuclear Regulatory Commission's Flexible Coping Strategies (FLEX) program, which states that nuclear power plants will have large-scale diesel generators with large-scale fuel capacity.[71] The FLEX program has taken several lessons learned from the Fukushima meltdown incident and mandated that nuclear power facilities in the United States implement steps to deal with a variety of external threats, especially the loss of offsite power.[72] For example, Browns Ferry Nuclear Power Plant alone has over 282,240 gallons of diesel fuel, and diesel generators at nuclear power facilities are in enclosed underground concrete structures, providing them some protection against electromagnetic events, but they would still need to be sufficiently hardened.[73] The FLEX program was not created specifically for EMP/GMD events but could extend power to the grid as a long-term option. Depending timing and how robust the movement to deploy small modular reactors (SMRs) is, these units, if EMP hardened, have great potential to serve as black start resources.[74]

Black start frameworks can provide policy makers and private sector leaders a strategy that would provide added resilience in a variety of contingencies, not just EMP/GMD events. Coordination between the DOE and utility companies may be the only way to provide for a stable national grid system in a post EMP/GMD environment. Black start options are the only known way to re-start the grid after it experiences a catastrophic failure. Initially, black start options could be used to provide power to regional areas but could then be used to transport power to other effected areas as most grid interconnections would still be intact. Utilizing Woods' concepts of robustness and graceful extensibility, EMP/GMD hardened black start options would be a key strategy for recovering from EMP/GMD events.

69 Greene, "Nuclear Power," 16.

70 Greene, 15.

71 Greene, 14.

72 Greene, 13.

73 Greene, 14.

74 Sherrell R. Greene, "How Nuclear Power Can Transform Electric Grid and Critical Infrastructure Resilience," *Journal of Critical Infrastructure Policy*, Fall/Winter 2020.

Conclusion

The results and analysis of both thought experiments prescribed significantly higher levels of preparedness at regional and local levels and the implementation of new and existing technology to add resilience to America's electrical infrastructure. As seen in the thought experiments, the loss of the electrical grid has significant cascading effects on other critical infrastructure sectors and the civilian population. Even as these events are very rare, they have the potential to produce detrimental effects to modern society by disabling vital everyday services that we all take for granted. Recent natural disasters such as Hurricane Ida and the 2021 Texas winter power outages have had adverse impacts on the population and should lower our confidence in our critical infrastructure systems, especially when dealing with events we are truly unprepared for. EMP/GMD events could make entire regions lose the ability to produce power and provide medical assistance, and could impede food/water production, putting enormous stress on the all levels of government.

As technology has rapidly advanced, modern society has become more reliant on the services it provides for almost every aspect of modern life. The more dependent society becomes on technology, the more vulnerable we are to a fundamental surprise when the electrical grid fails to operate reliably. There is little doubt that technology has transformed most modern countries into a reality were almost anything can be found or delivered via the internet or some other form of wireless communication device. Huge parts of our critical infrastructure systems are tied into wireless internet systems and are at risk of not just cyber-attacks, but also electromagnetic events. This article does not argue that we must abandon humanity's quest for more technology; it argues that we must have systems in place in case a long-term power outage event occurs because of an electromagnetic event and that a foundation of preparedness at the lowest level will be advantageous to the recovery effort.

Despite well-studied and known vulnerabilities of some systems to EMP/GMD events, we were able to use thought experiments to identify certain decision-making factors that influence national resilience. By analyzing how EMP and GMD events occur and how we are likely to respond, recommendations were made in order to mitigate the effects of these events. Utilizing the SAAL and Woods' frameworks, we found that through a combination of policy changes, such as focusing preparedness at local levels and better communication between the DOD and DHS, together with technological innovations such as hardened microgrids and black start options, there are ways to mitigate the threat of EMP/GMD events.

Acronyms and Abbreviations

CME	Coronal Mass Ejection
DOD	Department of Defense
DOE	Department of Energy
EMP	Electromagnetic Pulse
FLEX	Regulatory Commission's Flexible Coping Strategies
GIC	Geomagnetically Induced Current
GMD	Geomagnetic Disturbance
NOAA	National Oceanic and Atmospheric Administration
SMR	Small Modular Reactor
SWPC	Space Weather Prediction Center

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