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THE ELECTROMAGNETIC THREAT TO THE UNITED STATES: RECOMMENDATIONS FOR CONSEQUENCE MANAGEMENT

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THESIS

THE ELECTROMAGNETIC THREAT TO THE UNITED STATES: RECOMMENDATIONS FOR CONSEQUENCE MANAGEMENT

by

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December 2021

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13. ABSTRACT (maximum 200 words)

This thesis analyzes the threat of both electromagnetic pulse (EMP) and geomagnetic disturbances (GMD) to the U.S. Department of Homeland Security. EMP/GMD events are classified as low-probability/high-impact events that have potential catastrophic consequences to all levels of government as well as the civilian population of the United States. By reviewing current literature and conducting two thought experiments, this thesis determined that various critical infrastructure sectors and modern society are at risk of the effects of EMP/GMD events. Some of the most serious consequences of a large-scale EMP/GMD event 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 introduced several recommendations that could be utilized by policymakers to mitigate the effects of EMP or GMD events. Some of the recommendations include utilizing hardened micro-grid systems, black start options, and various changes to government agency organizations that would provide additional resilience and recovery to American critical infrastructure systems in a post-EMP/GMD environment.

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THE ELECTROMAGNETIC THREAT TO THE UNITED STATES: RECOMMENDATIONS FOR CONSEQUENCE MANAGEMENT

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LIST OF ACRONYMS AND ABBREVIATIONS

CME	Corneal Mass Ejection
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
EMP	Electromagnetic Pulse
FLEX	Flexible Coping Strategies
GMD	Geomagnetic Disturbance
SCADA	Supervisory Control and Data Acquisition

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I. INTRODUCTION

A. MAJOR RESEARCH QUESTION

Intelligence officials, scientific experts, and blue-ribbon commissions have warned about the threat that an electromagnetic pulse (EMP) could pose to the United States. Some assessments have warned that an EMP attack from a nuclear blast or geomagnetic disturbance (GMD) could shut down the national electrical systems and other key critical infrastructures for over a year, which would have disastrous second-and-third order effects to the national security of the United States. An EMP or a GMD event would be classified as a low-probability, high-impact crisis that could result in an enormous number of casualties that would make the COVID-19 pandemic quite small in comparison. This thesis asks two questions: How ready is the United States for an EMP/GMD event, and what additional steps might help the Departments of Homeland Security, Energy, and Defense to further mitigate and improve resilience to this threat?

B. SIGNIFICANCE OF THE RESEARCH QUESTION

An EMP is an electromagnetic wave generated from man-made devices, where 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 are 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.[1] 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 any device vulnerable to electrical surge, such as computers, cell phones, servers, switchgear, lighting, transformers, and control systems among many others, can be destroyed due to EMP/GMD. Importantly,

[1] 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.

EMP and GMD can affect large geospatial regions when generated from nuclear weapons or a coronal mass ejection, such that entire 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 and supervisory control and data acquisition (SCADA) system technology. Whether this event 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 amounts of causalities.

Modern society has benefited greatly from advances in communications, computer technology, and modern electrical grids. American citizens, government agencies, and business firms all rely heavily on various forms of technology that connect the world though systems of technological networks. These networks are powered by dedicated electrical grid systems throughout the United States that support vital critical infrastructure sectors and the American way of life. The electrical grid, which we depend on to be more connected in every way possible, is at risk to EMP. Experts warn that an EMP or GMD event would create long-term consequences to the United States and would completely change this nation's position on the world stage.

While the impact of an EMP event varies based on several factors such as location, intensity, and time of day, the worst-case scenario would be an EMP/GMD event that permanently disables all electronic equipment within the affected area. This scenario would also involve the loss of basic levels of communication, emergency services, transportation, and medical treatment that citizens utilize on a daily basis. Other scenarios involve only a temporary loss of small systems such as cell phones or computers, which may be less impactful. Still, some key electrical grid component, such as extra high voltage (EHV) transformers in regional transmission, are likely to fail given an EMP/GMD of any kind. The loss of a few EHV transformers can lead to large-scale impacts due to the interconnected nature of the power transmission and distribution systems, as blackouts can cascade and damage or destroy power grids and independent infrastructure that reside outside the EMP/GMD area.[2] In addition, recovery would be extremely difficult as many vital components of the power system, such as EHV transformers, are produced outside the United States and take 12–24 months to acquire under normal conditions, much less in a state of emergency.[3]

SCADA systems are critical computer systems that monitor and control all modern electric, water, and transportation systems that are also vulnerable to EMP/GMD events. Put simply, SCADA systems are used to control vast systems of data acquisition and infrastructure over large geographical areas.[4] SCADA systems provide the ability to monitor changes to the status of various sub systems and adjust as the situation dictates without the need for human interaction. SCADA technology manages hundreds of commands and system diagnostics to ensure critical infrastructure sectors provide the necessary services to American citizens. Modern SCADA systems are at risk from EMP/GMD events due to their exposed antenna structures which would be susceptible to the overvoltage of an EMP event.[5] If SCADA systems were brought offline or destroyed by an EMP or GMD event, entire critical infrastructure control sectors would be disabled.

Past events where a coronal mass ejection (CME) led to widespread infrastructure failures motivate efforts 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.[6] 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.[7] Given that

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[2] Matthew Weiss and Martin Weiss, "An Assessment of Threats to the American Power Grid," *Energy, Sustainability and Society* 9, no. 1 (2019): 3–9, https://doi.org/10.1186/s13705-019-0199-y.

[3] Weiss and Weiss, 2.

[4] 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), 5, https://apps.dtic.mil/sti/citations/ADA484672.

[5] Foster Jr. et al., 4.

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

[7] Hapgood, 7.

the power grids in the United States have not been reinforced for modern EMP or GMP threats, reliance on electrical grids has advanced tremendously in the United States since 1989, and data, control, and telecommunications devices are now ubiquitous across infrastructure system operations, a similar GMD event today may result in even greater damage to electrical systems.[8]

From a federal government perspective, an EMP/GMD event would create an enormous burden for key agencies such as the Department of Homeland Security (DHS), Department of Energy (DOE), and the Department of Defense (DOD) as they all play a critical role in coordinating risk mitigation and post event coordination with state and local agencies. American society would be severely disrupted by a long-term loss of electrical systems that would have cascading effects that would have severe societal implications and enormous loss of life. A report from the Department of Homeland Security states

> The impacts to critical infrastructure resulting from electromagnetic incidents differ significantly from other large-scale, naturally occurring hazards, such as hurricanes…These effects may simultaneously damage critical energy distribution nodes and industrial control systems over wide geographic areas though damage to microprocessors and power transformers. Such simultaneous disruptions over large areas of the country would likely undermine the implementation of mutual aid plans and agreements, a cornerstone of our approach to disaster response.[9]

Given the large-scale, low-probability, and widespread physical and governance impacts of EMP/GMD, the recommended way to manage future events is through improving national *resilience.* The U.S. federal government defines resilience in Presidential Policy Directive 21 as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions…to withstand and recover from deliberate attacks, incidents, or naturally occurring threats or incidents."[10] Improving

[8] Weiss and Weiss, "An Assessment of Threats to the American Power Grid," 3.

[9] 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), 5, https://www.hsdl.org/?abstract&did=817225.

[10] Barack Obama, *Presidential Policy Directive 21: Critical Infrastructure Security and Resilience*, PPD 21 (Washington, D.C: United States. White House Office, 2013), 5, https://www.hsdl.org/?abstract&did=731087.

resilience has been the primary way government agencies like DHS manage high impact, low probability events since initial recognition of the possibility of large-scale infrastructure failures by the Presidential Commission on Critical Infrastructure Protection in 1997.[11] The recent Executive Order 13865 follows this approach, with the aim to coordinate government agencies to improve national resilience to EMP/GMD threats.[12]

One approach to help public and private entities assess and improve resilience to an EMP/GMD threat is though *resilience engineering,* or designing resilience into our national infrastructure and governance systems.[13] Resilience engineering is a field of study that promotes the analysis of the "dynamic interactions among systems that rely on human abilities to learn from prior experiences, and to anticipate possible conditions and outcomes,"[14] with the goal to protect and adapt systems before and after disasters.[15] Utilizing resilience engineering concepts and frameworks provides a basis to assess the current capacities and capabilities government agencies and public utilities have to mitigate or withstand an EMP/GMD. For example, past studies in resilience engineering improve how organizations reacted to and anticipated disaster events based on prior knowledge and contingency planning exercises.[16] While government agencies and private utility companies may understand what an EMP/GMD event is from a scientific perspective, they may not have a clear understanding of their current and future ability to adapt critical

[11] Bill Clinton, *Presidential Decision Directive 63: Protecting America's Critical Infrastructures*, PPD 63 (U.S. Department of State, 1998), 2–4, https://www.hsdl.org/?abstract&did=3544.

[12] "Executive Order 13865-Coordinating National Resilience to Electromagnetic Pulses," Government, govinfo.gov (Office of the Federal Register, National Archives and Records Administration, March 26, 2019), https://www.govinfo.gov/app/details/https%3A%2F%2Fwww.govinfo.gov%2Fapp%2Fdetails%2FDCPD-201900176.

[13] Igor Linkov et al., "Changing the Resilience Paradigm," *Nature Climate Change* 4, no. 6 (June 2014): 407–9, https://doi.org/10.1038/nclimate2227.

[14] 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): 4, https://doi.org/10.1515/jhsem-2017-0019.

[15] David D. Woods, "Four Concepts for Resilience and the Implications for the Future of Resilience Engineering," *Reliability Engineering & System Safety* 141 (September 2015): 2, https://doi.org/10.1016/j.ress.2015.03.018.

[16] Thomas et al., "A Resilience Engineering Approach to Integrating Human and Socio-Technical System Capacities and Processes for National Infrastructure Resilience," 1.

infrastructure systems and processes if an EMP/GMD occurred. Resilience engineering frameworks provide a basis for policymakers and system operators to assess resilience in current critical infrastructure systems and identify ways to adapt to surprising threats like an EMP/GMD event.

C. LITERATURE REVIEW

There is a substantial amount of literature on EMP events that describe the threat and potential consequences to America's critical infrastructure and society. Many sources explain that while many government agencies such as the Department of Defense and Homeland Security have taken steps to try and mitigate the effects of an EMP/GMD event, some civilian infrastructure sectors have not implemented EMP/GMD mitigation techniques and could be vulnerable to both a naturally occurring GMD threat or an adversarial EMP attack.[17] This literature review is broken into three sections: The first section demonstrates that the United States has significant vulnerabilities to the effects of an EMP/GMD event, the second section examines mitigation techniques that can be utilized to combat the effects of an EMP/GMD event, and the third section will explore resilience frameworks that can be used to develop research methodologies that investigate how humans and systems can prepare and withstand the effects of EMP/GMD events.

1. Is the United States Prepared for an EMP/GMD Event?

Many sources conclude that the United States' infrastructure and society is unprepared for EMP/GMD events. Studies have shown that EMP/GMD events can cause serious malfunctions or even destroy modern power transmission lines and transformers and could potentially collapse large portions of the electrical grid as many key components are not designed or intended to withstand electromagnetic events.[18] Because of the overwhelming reliance on power grids, EMP/GMD events can have significant impacts on water, transportation, emergency satellite communications, internet and SCADA systems

[17] Weiss and Weiss, "An Assessment of Threats to the American Power Grid," 3.

[18] Dingwei Wang et al., "Power Grid Resilience to Electromagnetic Pulse (EMP) Disturbances: A Literature Review," in *2019 IEEE Conference on Electromagnetic Disturbances* (Washington, D.C: IEEE, 2019), 3, https://doi.org/10.1109/NAPS46351.2019.9000227.

due to the extreme overvoltage that has damaging effects to all of these systems.[19] Some argue "No other infrastructure other than electric power has the potential for nearly complete collapse in the event of a sufficiently robust EMP attack."[20] In terms of preparedness, sources state that there is still much to be done in terms of hardening and resilience planning for the electrical grid as many of these systems are at risk of EMP/ GMD events."[21] In addition to SCADA systems, key infrastructure that is equipped with back-up generation units are only able to operate for a limited amount of time and are not a suitable solution to EMP/GMD events as blackouts may last for weeks or months.

Some experts explain that the standards by which some private sector entities operate is putting the United States at risk, especially against naturally occurring GMDs. Wiess and Wiess write that power companies abide by a standard set by the Federal Energy Regulatory Commission (FERC) which downplays the potential damage of an EMP/GMD event.[22] According to their article, FERC standards for power companies are only set to withstand GMD levels of recent storms, such as the Quebec storm in 1989 which produced 8 volts per kilometer (V/KM), which is the standard measurement for electric current in the atmosphere.[23] These precautions do not account for events such as the 1859 Carrington level storm that destroyed telegraph lines on the earth surface, which included voltages of over 13.6 V/KM.[24] According to these figures, power companies that abide by FERC standards may not be able to withstand significant GMD events and put the energy infrastructure at risk. Expert suggest that if a major Carrington level storm occurred today, the damage would cause 1–2 trillion dollars and a recovery period of four to ten years.[25] Furthermore, the energy community has no plan to deal with the long-term consequences of power loss in terms of water purification, food shortages, and sanitation issues such as

[19] Wang et al., 3.

[20] Wang et al., 3.

[21] Wang et al., 6.

[22] Weiss and Weiss, "An Assessment of Threats to the American Power Grid," 3.

[23] Weiss and Weiss, 2.

[24] Weiss and Weiss, 3.

[25] Weiss and Weiss, 2.

cholera.[26] The Wiess article also found that SCADA systems were the single point of failure in many critical infrastructure sectors as they failed every test where they were exposed to a "simulated EMP environment."[27]

In addition to damage to critical infrastructure, some reports have showcased possible economic impacts of EMP/GMD events. Researchers found that a naturally occurring GMD event could have substantial impacts on global supply chains and result in the loss of up to 5.6 percent of the global GDP.[28] Additional research also indicated that, based on predictive models of space weather events, the Northwestern United States and Central Europe were most likely to be impacted by a GMD event, which has significant implications due to the global economic importance that resides within those regions.[29]

The "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack" is one of the most informative sources on the impact of EMP/GMD events on various critical infrastructure sectors. The EMP commission was a congressionally mandated investigative body that assessed the vulnerability of United States infrastructure against an EMP attack and included recommendations to mitigate the effects of EMP/GMD events. While the report goes in depth on all critical infrastructure sectors, the most profound findings on vulnerabilities are found in the electric power section. The report states "Contemporary U.S. society is not structured, nor does it have the means, to provide for the needs of nearly 300 million Americans without electricity. Continued electrical supply is necessary for sustaining water supplies, production and distribution of food, fuel, communications, and everything else that is part of our economy."[30] Based on the report's analysis, almost every part of American life is dependent on the electric grid to remain operational. In addition, the report details how

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26 Weiss and Weiss, 7.

27 Weiss and Weiss, 5.

28 H. Schulte in den Bäumen et al., "How Severe Space Weather Can Disrupt Global Supply Chains," *Natural Hazards and Earth System Sciences* 14, no. 10 (October 10, 2014): 2749–59, https://doi.org/10.5194/nhess-14-2749-2014. 8

29 Schulte in den Bäumen et al., 8.

30 Foster Jr. et al., *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack*, 10.

reliant American society is on the electrical grid and claims that if the grid were to go offline for two weeks, there could be substantial loss of life due to cascading effects.[31] According to the Commission's findings, the United States power grid is vulnerable of EMP/GMD events due to the interconnective nature of the power grid, vulnerabilities of SCADA control systems, and the decreasing amount of backup power systems available for emergencies and restoration.[32]

According Dr. Peter Pry, the Executive Director of the Task Force on National and Homeland Security, Russia, China, Iran, and North Korea have implemented the effects of an EMP attack into their military doctrine.[33] Russia in particular has created the concept of "Non-Contact Wars" and "Sixth Generation Warfare" where a combination of cyber-attacks with nuclear and non-nuclear EMP strikes would cripple its target without having to commit ground forces or use traditional kinetic weapons.[34] Additional reports from the Department of Defense also indicate the effects of enemy EMP threats have become even more exacerbated because the United States continues to field 5G communication technologies that are less resilient to EMP pulses and present a larger problem set that at best case would disable cell phone coverage in affected area and worse case could include total communications blackout.[35]

There are several counterarguments that downplay the seriousness of EMP threats as many experts deem these threats to be unlikely. Kelsey Atherton argues in Foreign Policy Magazine that it is unrealistic to expect a state or non-state actor to use a nuclear

31 Foster Jr. et al., 32.

32 Foster Jr. et al., 24,30.

33 Peter Pry, *Nuclear EMP Attack Scenarios and Combined-Arms Cyber Warfare*, Report to the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack (Washington, D.C: United States Government, 2017), 2.

34 Pry, 1.

35 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), 5, https://www.hsdl.org/?abstract&did=828407.

device only for its EMP effects and disregard its destructive capabilities.[36] Atherton's piece also explains that the United States military has solved the EMP problem as it has hardened its nuclear command and control systems and has shared this information with the civilian sector.[37] Other experts have noted that it is impractical for non-state actors to have the expertise or capability to even acquire a nuclear weapon in the first place, much less produce an EMP.[38] Another counterargument is suspicious of the North Korean EMP threat as some experts conclude that North Korea does not possess the expertise or technological assets to use an EMP in an offensive manner.[39] Most counterarguments conclude that an adversarial EMP attack is unlikely because of the complicated nature of using a nuclear weapon for such an attack and a more likely scenario would come from a naturally occurring solar GMD event, caused damage to electrical systems in the past events.[40]

2. Means Available to Mitigate the EMP/GMD Threat

Some government agencies are developing mitigating strategies to combat the EMP/GMD threat. The Department of Energy (DOE) has published a strategic plan that explains specific courses of action and mitigation techniques to counter EMP/GMD threats. According to the DOE, the primary mitigation effort consists of post-event coordination and information sharing with the private sector, which assumes that secure lines of communications between public and private entities are pre-established prior to any EMP/

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[36] Kelsey D. Atherton, "Electromagnetic Pulses Are the Last Thing You Need to Worry About in a Nuclear Explosion," *Foreign Policy*, July 21, 2020, 6, https://foreignpolicy.com/2020/07/21/electromagnetic-pulses-emp-weapons-nuclear-explosion/.

[37] Atherton, 2.

[38] Nick Schwellenbach, "Empty Threat?," *Bulletin of the Atomic Scientists* 61, no. 5 (September 2005): 54, https://doi.org/10.1080/00963402.2005.11460920.

[39] Elizabeth Jensen, "LOL At EMPs? Science Report Tackles Likelihood of A North Korea Nuclear Capability," *National Public Radio*, May 30, 2017, https://www.npr.org/sections/publiceditor/2017/05/30/530262884/lol-at-emps-science-report-tackles-likelihood-of-a-north-korea-nuclear-capabilit.

[40] Yousaf Butt, "The EMP Threat: Fact, Fiction, and Response (Part 1)," *The Space Review*, January 25, 2010, https://www.thespacereview.com/article/1549/1.

GMD event occurring.[41] This strategy includes information sharing with other government agencies and private sector companies to provide both classified and unclassified information on EMP waveform and hardening procedures so that both government and non-governmental organizations can set and share standards.[42] A 2016 report from the Government Accountability Office (GAO) also assessed that government agencies are taking steps to mitigate this threat.[43] According to a GAO report, the Department of Homeland Security, Department of Energy, and Federal Energy Regulatory Commission have taken several actions to create standards and guidelines to protect government and civilian infrastructure against EMP/GMD events.[44] In addition, several of these agencies have followed the recommendations of the EMP Commission and continue to refine strategies that deal with the protection of critical infrastructure and post-event coordination.[45] Although the report lists some positive aspects of EMP preparedness from several government agencies, it also states that there are significant gaps between government and private sector coordination and information sharing among government entities.[46] In 2019, the Trump administration mandated that various government agencies, mainly the Department of Homeland Security, take steps to combat the EMP threat to the United States but it remains unclear how effective those mitigation efforts will be or if they will remain in place under the new Biden Administration.

The Electric Infrastructure Security Council (EIS) has developed some unconventional solutions to mitigate what EIS labels as "Black Sky Events" that include EMP/GMD scenarios. One report, called "Black Sky, Black Start Protection Initiative,"

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[41] Department of Energy, *U.S. Department of Energy Electromagnetic Pulse Resilience Action Plan*, EMP Pulse Report 1 (Washington, D.C: Department of Energy, 2017), 8, https://www.hsdl.org/?abstract&did=.

[42] Department of Energy, 8.

[43] U.S. Government Accountability Office, *Critical Infrastructure Protection: Federal Agencies Have Taken Actions to Address Electromagnetic Risks, but Opportunities Exist to Further Assess Risks and Strengthen Collaboration, Report to Congressional Requesters*, GAO-16-243 (Washington, D.C: U.S. Government Accountability Office, 2016), 2, https://www.hsdl.org/?abstract&did=.

[44] U.S. Government Accountability Office, 2.

[45] U.S. Government Accountability Office, 2.

[46] U.S. Government Accountability Office, 2.

lists several strategies for mitigating the effects of EMP/GMD events. The "Black Start Initiative" calls for the EMP hardening of secure enclaves of primary of backup power generation or transmission sites in strategic locations that would provide emergency power if the electrical grid were to fail for an extended period of time.[47] The EIS report also recommends that the energy sector utilize decommissioned coal power facilities and transition them into gas turbine power centers as large-scale backup systems that can provide long term emergency power in case large portions of the electrical grid are taken offline.[48]

Some experts argue that there are various methods to protect electronic equipment from the EMP/GMD effects.[49] While some of the methods mentioned are very technical, certain methods are as easy as utilizing surge protectors and antenna protection techniques, which are common protections used for lightning strikes that occur near powerlines. In addition, post-event mitigation strategies that include early detection and response plans, the proliferation of hardening techniques and EMP threats to the private sector, and planning for fast repair, storage of critical spare parts, and coordination between all levels of government.[50]

Other means that are being developed to mitigate the effects of EMP/GMD events include state of the art experimental software modeling. A technical article from Cornell University showcased new software applications that can be used for modeling and simulations of a EMP/GMD events that could lead researchers to better understand how to protect critical electrical infrastructure.[51] This type of technology is still being developed but could lead to promising solutions that involve using experimental software that enables electrical power SCADA systems to adjust power systems in a way that mitigates the

[47] "Black, Sky, Black Start Protection Initiative," Electric Infrastructure Security Council, accessed July 22, 2021, https://www.eiscouncil.org/App_Data/Upload/BSPI.pdf.

[48] Electric Infrastructure Security Council.

[49] Wang et al., "Power Grid Resilience to Electromagnetic Pulse (EMP) Disturbances," 5.

[50] Wang et al., 5.

[51] Adam Mate et al., *Analyzing and Mitigating the Impacts of GMD and EMP Events on the Electrical Grid with PowerModelsGMD.Jl*, LA-UR-19-29623 (Ithaca, New York: Cornell University, 2021), 1, http://arxiv.org/abs/2101.05042.

effects of currents produced by EMP events.[52] The software is able to communicate data to large electric transformers to adjust power, output, and heating based on the electrical current that is being produced by an EMP event.[53]

3. Resilience Concepts and Frameworks

Given the widespread recognition that the United States is vulnerable to EMP/GMD, the efficacy of these plans, analyses, and tools for managing future events is unclear. Here, resilience concepts and frameworks can assist policymakers and human operators in creating systems that are designed to survive and recover from stressful environmental events before they occur. Resilience is a familiar concept to the national strategy of the United States. 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.[54] The United States now prepares for unexpected events using resilience concepts, especially when involving homeland defense and security of critical infrastructure systems.[55] Resilience goals and practices are commonplace among many federal agencies that would be involved in EMP/GMD response and recovery, including DHS,[56] the Department of Commerce,[57] the DOD, and the DOE[58] among many others.

Despite widespread recognition of need for resilience among U.S. government agencies, large-scale infrastructure failures continue to occur meaning that systems are not resilient. Alderson suggests that there are at least four barriers inhibiting national resilience

[52] Mate et al., 1.

[53] Mate et al., 1.

[54] Obama, *Presidential Policy Directive 21*, 2.

[55] 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.

[56] Department of Homeland Security, *Strategy for Protecting and Preparing the Homeland Against Threats of Electromagnetic Pulse and Geomagnetic Disturbances*.

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

[58] Department of Energy, *U.S. Department of Energy Electromagnetic Pulse Resilience Action Plan*, 20.

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.[59] Alderson argues that overcoming these barriers requires a need to draw upon work in resilience engineering to guide organizational policies and missions.[60]

Specifically, resilience frameworks implemented in many federal agencies focus on improving disaster management by planning for, absorbing, recovering from, and adapting to stressful events.[61] Yet this approach overemphasizes predefined threats (barrier 2), does not improve our understanding of real systems and data sharing (barrier 3), and does not relate to a large amount of resilience theory and literature (barrier 4). In contrast, resilience engineering literature focuses less on improving existing disaster management practices to known threats and more on the social and technological limitations for systems to recognize and adapt to surprising events that are not easy to predict.[62] Related resilience engineering concepts and frameworks provide an important way to assess the efficacy of existing practices for managing future EMP/GMD events that may inevitably surprise national infrastructure systems.

There are two frameworks developed within the resilience engineering technical community for assessing and improving current resilience practices concerning EMP/GMD events. First, resilience engineering literature suggest that government agencies and utility operators must prepare for uncertain events by incorporating the sensing, anticipating, adapting, and learning process (SAAL).[63] The SAAL process describes how

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[59] 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.

[60] Alderson, 76.

[61] Sabrina Larkin et al., "Benchmarking Agency and Organizational Practices in Resilience Decision Making," *Environment Systems and Decisions* 35, no. 2 (June 2015): 187, https://doi.org/10.1007/s10669-015-9554-5.

[62] Daniel Eisenberg, Thomas Seager, and David L. Alderson, "Rethinking Resilience Analytics," *Risk Analysis* 39, no. 9 (2019): 2, https://doi.org/10.1111/risa.13328.

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

technological systems and human cognitive nature interact to maintain a certain level of function during stressful events that are either expected or unexpected.[64] The SAAL process are:

- **Sensing**- "the process to apprehend and interpret information about a system's operations status relative to known and unknown vulnerabilities and system shocks"[65]
- **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"[66]
- **Adapting**- "describes the process governing system responses to both known and unknown changes in stability and operating performance"[67]
- **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."[68]

Improving 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.

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,"[69] that categorize outcomes witnessed when systems survive unexpected stressful events. The four concepts are:

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[64] Thomas et al., 6.

[65] Thomas et al., 7.

[66] Thomas et al., 7.

[67] Thomas et al., 7.

[68] Thomas et al., 7.

[69] Woods, "Four Concepts for Resilience and the Implications for the Future of Resilience Engineering," 1.

- **Rebound**- how a system rebound back 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.[70]

Woods' four concepts can assist with the understanding and creation of resilient systems, mainly critical infrastructure, that has the ability to withstand known and unknown events and ensure 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.

D. POTENTIAL EXPLANATIONS AND HYPOTHESES

The United States is unprepared to deal with the effects of a large- scale EMP/GMD due to the fact that the vast majority of civilian electrical critical infrastructure is not hardened against the most severe EMP/GMD events. While some government facilities and infrastructure have been hardened to withstand electromagnetic events, it is likely that the vast majority of civilian infrastructure is vulnerable and would be either taken offline or permanently damaged if an EMP/GMD event were to occur due to the lack of resilience that resides within our electrical infrastructure.

Based on the amount of damage that was sustained by Canadian and American electrical grids during the 1989 Quebec GMD event, even greater damage would ensue from a similar event occurred based on the current reliance on wireless technology and SCADA systems. In addition, it is not clear whether private power utility companies are

[70] Woods, 1–2.

equipped to withstand EMP/GMD events or follow FERC standards as the electrical infrastructure of the United States is routinely damaged and taken offline by reoccurring natural disasters. A recent example of a large-scale grid failure occurred in Texas when an unusual occurrence of arctic weather disabled both wind turbine and natural gas systems.[71] The Texas power grid failure example demonstrates what can happen when power grids are managed by private companies that have limited public oversight and are forced to compete in competitive markets.[72] There is a greater incentive to provide power services in the cheapest manner rather than provide a reliable power grid that is resilient to known and unknown threats. An even more startling example of how private entities are at risk of external threats is the Colonial Pipeline cyber-attack where hackers used ransomware to take control of the pipeline that resulted in numerous gas shortages throughout the Southeastern United States. In comparison, even a small scale EMP/GMD event could disable numerous power transformers that could result a cascading shortage of gas which would have disastrous long-term economic consequences.

Various government agencies have taken steps to mitigate against EMP/GMD events, but many of these mitigation techniques have not proliferated to the private sector, which constitutes the primary operators of the electrical grid. Again, evidence suggests that because power utility companies are privately owned, it is entirely possible that hardening the grid against EMP/GMD would require more resources than most utility companies can provide while still being competitive in the market. The problem resides with the regulation and relationship between private utility companies and government agencies. A large-scale EMP/GMD event, based on the current state of the United States' power grid, could potentially cause large-scale electrical blackouts that would put enormous stress on power utility companies and government agencies based on the regulatory relationship between the public and private sector. Both government agencies and private utilities need to create

[71] 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.

[72] Halper.

a more collaborative environment where EMP hardening techniques are shared and implemented to ensure all entities can meet an acceptable standard of EMP protection.

E. RESEARCH DESIGN

This thesis will compare two case studies--the 1869 Carrington GMD event and the 1962 USSR EMP test which was conducted specifically to understand how electromagnetic forces interact with electrical systems--to determine how a large-scale electromagnetic event would affect modern-day electrical systems and infrastructure.[73] The thesis will utilize a thought experiment methodology,[74] to aid in conceptional analysis, combined with elements the SAAL framework, to understand how present-day systems and organizations would react and operate when considering the EMP/GMD environment of the case studies.[75]

The SAAL framework will aid in understanding how present-day systems and infrastructure will react to changing environmental factors that occurred in each case study. Utilizing this framework, the thesis will investigate what courses of actions are available to both public and private policymakers when responding to the threat and post event consequences of an EMP/GMD event. This type of resilience engineering approach will aid in simulating realistic outcomes which would and help readers understand how prepared or unprepared the United States is for an EMP/GMD event.

Based on the outcomes of the case studies, this thesis will also utilize the Woods's four concepts of resilience engineering to evaluate current mitigation techniques, such as FERC grid hardening regulations for EMP events, and recommend future policies that would protect infrastructure against EMP/GMD threats. For example, using resilience concepts from the Woods paradigm, government agencies could develop shielding techniques to protect critical infrastructure systems to ensure they could sustain function

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

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

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

during EMP/GMD events, improving robustness and survivability of these systems. Using this model, the thesis will be able to measure what mitigation efforts are effective and resilient enough to potentially withstand or resurrect critical infrastructure systems from an EMP/GMD event.

F. THESIS OVERVIEW AND DRAFT CHAPTER OUTLINE

The first chapter of the thesis focuses on the importance, literature review, and the introduction of my argument. Chapter II concentrates on defining the EMP and GMD threat and explains the scientific process that takes place when these events occur. Chapter III takes an in depth look at each case study, using a thought experiment methodology, and explains how these events demonstrate how vulnerable the U.S. power grid and society is to EMP/GMD events. Chapter IV analyzes the case studies utilizing the SAAL framework and makes recommendations to mitigate against the EMP/GMD threat. Chapter V introduces the Woods resilience frameworks and how they can be applied to create systems and processes that are more resilient against the EMP/GMD threat. Chapter VI presents the conclusion that determines how prepared the United States is for an EMP/GMD event and what mitigation measures can be realistically implemented. Chapter VI also recommends areas of future research.

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II. EMP/GMD EVENTS EXPLAINED

The purpose of this chapter is to provide a more in-depth explanation of what EMPs/GMDs are, how they occur, and explain how these events can interrupt electric power systems and produce significant second-and-third order effects on modern society. EMPs and GMDs are popular subjects in many works of fiction, in which they often act as the catalyst for massive post-apocalyptic event. The novel *One Second After* provides a horrific portrayal of the United States as it becomes crippled after a high altitude EMP destroys all electronics and creates a total breakdown of modern society.[76] From a homeland security perspective, novels such as *One Second After* offer unique thought-provoking scenarios to help planners and policy makers visualize how EMP/GMD events could affect the United States, however, most regional and local communities are consumed with other present-day issues such as the COVID-19 response, natural disasters such as fires, or the increase of violent crime, which puts electromagnetic events far outside the main concerns of most state and local governments. The first part of this chapter will provide a quick history of GMD events and also provide analysis on how GMDs interact with electrical systems. The second part of this chapter will explain how EMP events were first discovered by scientists and then provide an in-depth analysis of how EMPs can damage electrical infrastructure.

A. GEOMAGNETIC DISTURBANCES

GMD events create disturbances in the Earth's magnetic field due to enhanced solar forces that interact with the space environment that surrounds Earth.[77] A large-scale GMD occurs when a CME forms on the surface of the sun and directs high energy particles towards Earth that have the potential to adversely affect GPS systems, satellite communications, and, in extreme cases, disable power grids on the Earth's surface.[78] The

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

77 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=.

78 Department of Homeland Security, 6.

National Oceanic and Atmospheric Administration (NOAA) rates solar events on a scale based on their potential impacts to space and land based systems.[79] A mild radiation event from the sun would be rated as a S scale, which would degrade satellite communication and high frequency radio transmissions while a major GMD event would be rated on the G scale, which has the potential to have serious impacts to power grids on the Earth's surface.[80] The most powerful G scale GMDs produce powerful geomagnetically induced currents (GIC)s that are similar to the effects of a man-made EMP weapons and can potentially create the same disabling effects to major power grids. The NOAA's Space and Weather center can track and analyze solar activity that may result in a GMD, which can provide between a 16–90-hour window of early warning before a GMD event would interact with the Earth's atmosphere.[81]

There have been several instances when GMD events occurred in the past, all of which transpired before the advent of modern technology and society's dependency on large-scale power grids and global communication services. The earliest recorded GMD event occurred in 1859 and is referred to as the Carrington Event, based on the observations of astronomer Richard Carrington.[82] The Carrington event was observed by several early astronomers at a time when telegraph communication was becoming standard practice of most modern countries.[83] The Carrington GMD had profound and spectacular events on Earth that included abnormally large Aurora Borealis sightings and destroyed over 20,000 km of telegraph lines due to the GIC that overloaded the nascent telegraph system.[84] Based on modern analysis and modeling techniques, 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 due to the heavy dependance of wireless SCADA systems, which can act a conductor to

[79] Department of Homeland Security, 1.

[80] Department of Homeland Security, 1.

[81] Department of Homeland Security, 1.

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

[83] Giegengack, 421.

[84] Giegengack, 423.

GICs, and potentially creates thermal vulnerabilities of modern electrical transformers that result from overheating when exposed to GICs .[85]

Also described in Ch. I, another large-scale GMD caused the collapse of the Canadian power grid and left over 6 million people without power for almost nine hours and also damaged power facilities in New Jersey and other parts of the northern latitudes in 1989.[86] The 1989 GMD is considered to be nowhere near the strength of the Carrington event but still had serious effects on large scale power grids.[87] Based on the damage sustained during 1989 storm, an even larger GMD event would have disastrous consequences on modern technology as our wireless systems are becoming more vulnerable to EMP events, especially 5G systems.[88]

GMDs remain a threat to modern society based on the data from historical events and because the sun will continue to produce CMEs that will eventually interact with the Earth's atmosphere. As our power grids become more advanced and private and public entities continue to rely on wireless data and telecommunication systems, we put our society at a greater risk of total collapse if a Carrington-sized GMD were to occur, and unfortunately it is only a matter of time. GMDs do not share the same characteristics as EMP events which may provide some protection to small electronic equipment, but large power transformers are especially vulnerable to GICs as the extra currents will produce voltages that are outside of most transformer operating ranges. Failure of these transformers could create disastrous second- and-third order effects on modern society to include large scale blackouts that would deprive society of medical care, fuel, transportation, and food production.[89]

On August 31st, 2012, the NASA STERO spacecraft, designed to monitor solar activity, observed one of the largest CMEs ever to be recorded, but luckily, this CME was

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85 Weiss and Weiss, "An Assessment of Threats to the American Power Grid," 2.

86 Mark H. MacAlester and William Murtagh, "Extreme Space Weather Impact: An Emergency Management Perspective," *Space Weather* 12, no. 8 (2014): 532, https://doi.org/10.1002/2014SW001095.

87 Weiss and Weiss, "An Assessment of Threats to the American Power Grid," 2.

88 Stuckenberg, Woolsey, and DeMaio, *Electromagnetic Defense Task Force 2.0*, 10.

89 MacAlester and Murtagh, "Extreme Space Weather Impact," 535.

not directed towards Earth. Had this event occurred one week earlier, a massive Carrington sized GMD would have impacted the Earth's atmosphere and could have potentially created disastrous effects on global power systems. See Figure 1 for the NASA photo of the 2012 CME.[90] As of 2020, the sun's magnetic field began a new 11-year cycle and will most likely reach its most dangerous level in 2025, such that Carrington level GMD events are more likely during that time period.[91] Solar events that result in GMDs pose a serious risk to national security and policy makers need to take steps to make power grids more resilient to electromagnetic events now in order to avoid a total grid collapse in the future.

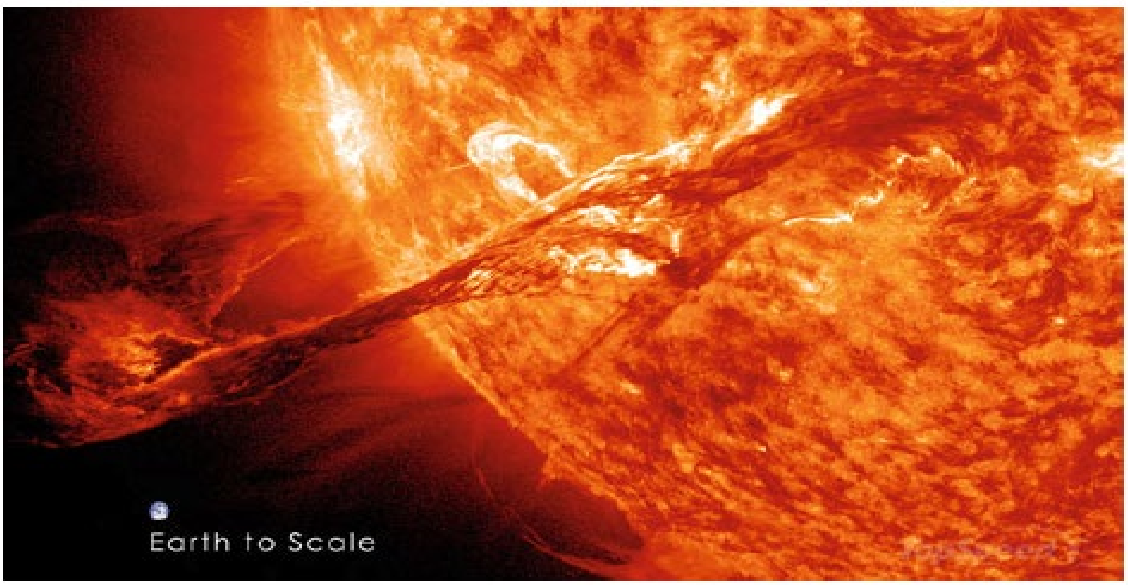

Figure 1. NASA photo of the 2012 CME[92]

GMD events have the potential to create significant issues for policy makers, government agencies, and the general public. It is extremely important that as researchers

[90] MacAlester and Murtagh, 530.

[91] Brian K. Sullivan, "Solar Storms Are Back, Threatening Life as We Know It on Earth," 13 April 2021, Bloomberg News, accessed July 11, 2021, https://phys.org/news/2021-05-solar-storms-threatening-life-earth.html.

[92] Carlos Alexandre Wuensche, "Fundamental Aspects of Coronal Mass Ejections," in *Handbook of Cosmic Hazards and Planetary Defense* (Switzerland: Springer International Publishing, 2015), 7, https://doi.org/10.1007/978-3-319-03952-7_7.

and scientist begin to uncover new details about these events, the public sector becomes more informed in order to assist in consequence management. A more prepared and resilient civilian population, that understands the second-and-third order effects of electromagnetic events, will assist in the mitigation and recovery if such an event did occur. Agencies such as Federal Emergency Management Agency (FEMA), who have an assigned mission to manage and mitigate natural and man-made disasters, will be greatly assisted when the civilian population has made necessary preparations for periods of long-term power loss, which may occur as a result of electromagnetic events.

As described previously, the U.S modern electrical power grid is the lifeline of all modern society and the source of energy for all other critical infrastructure areas.[93] Without reliable power generation and distribution systems, many parts of American society that people take for granted would cease to exist. For context, Figure 2 provides an overview of the functions the electrical power grid enables across all other critical infrastructure sectors in the United States.

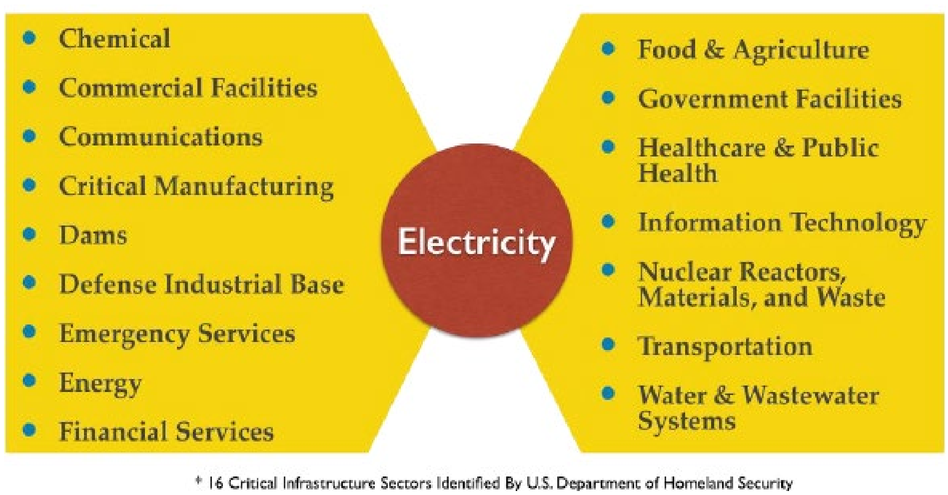

Figure 2. List of sectors that require electric power supplied by the U.S. electrical grid. Produced by the U.S. Department of Homeland Security[94]

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

[94] Greene, 3.

Currently, the U.S. power grid exhibits certain vulnerabilities to the effects of GMD events, specifically the GICs, which can overwhelm modern transformers and potentially cause permanent damage.[95] Simulations and computer models have attempted to locate the most vulnerable geographical areas of the of the U.S. power grid by identifying at-risk transformer locations and examined the potential cascading effects that could lead to system collapse.[96] Figure 3 illustrates that if a GMD event occurred, the cascading effects could disable at-risk transformers in the Northwest and East Coast, which could result in large geographic power blackouts throughout the country. This type of event would also create secondary cascading effects to other critical infrastructure sectors due to overcurrent damaging equipment and loss of power.

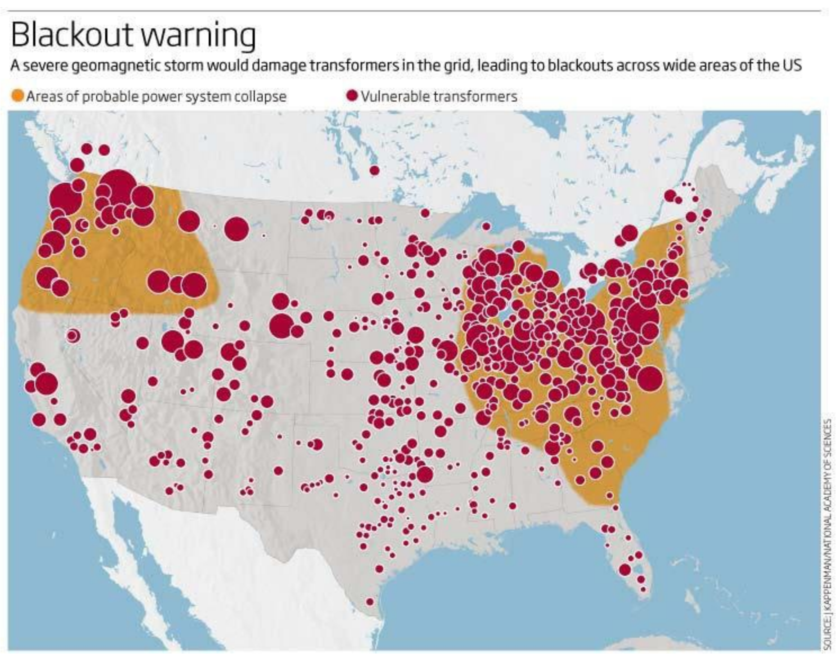

Figure 3. Map depicting transformers vulnerable to GICs (red) and possible blackouts due to transformer failure (yellow)[97]

95 Phylicia Cicilio et al., "Resilience in an Evolving Electrical Grid," *Energies (Basel)* 14, no. 3 (January 2021): 10, https://doi.org/10.3390/en14030694.

96 Krzysztof Lewandowski, "Protection of the Smart City against CME," *Transportation Research Procedia* 16, no. 1 (March 2016): 298–312, https://doi.org/10.1016/j.trpro.2016.11.029.

97 Lewandowski, 304.

One of the most widely used methods to mitigate damage from GMD are GIC blocking devices that can be placed between the transformer and the substation grounding.[98] These devices, while useful, are relatively expensive and could not be used to protect the entire grid due to the massive number of transformers that exist.[99] Also, transformers that are equipped with GIC-blocking devices can inadvertently overload other unprotected transformers which would have cascading effects on other parts of the grid.[100] Other simulations have indicated that not all transformers are at risk of GICs caused by a GMD event, but transformer systems that are on the edge of a network of geographical area are most at risk of being affected by the GIC.[101]

While there have been advances in technology to help protect electrical infrastructure against GMD events, many of these techniques are based on computer modeling and may not be an accurate representation of how an actual GMD event would affect electrical infrastructure.[102] Policymakers and grid operators may have to decide what electric infrastructure to save, by shutting down the systems, and what infrastructure to sacrifice in order to provide power to critical areas such as major population centers, large hospital systems, or key government facilities.

B. ELECTROMAGNETIC PULSE

The effects of EMP events on electrical systems were first understood by scientists during both the U.S. and Soviet nuclear testing in the 1960s.[103] After the United States initiated the Starfish nuclear test in 1962, which was detonated 400 km above Johnson Island in the Pacific Ocean, the effects of the EMP were experienced by the local population of the Hawaiian Islands, which are over 1400 miles away.[104] The EMP from the Starfish test caused

[98] Cicilio et al., "Resilience in an Evolving Electrical Grid," 11.

[99] Cicilio et al., 11.

[100] Cicilio et al., 12.

[101] Cicilio et al., 11.

[102] Cicilio et al., 11.

[103] Foster Jr. et al., *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack*, 4.

[104] Foster Jr. et al., 4.

burned out streetlights, tripped circuit breakers, and damaged military communication installations throughout the region.[105] In the same year, Soviet nuclear testing yielded similar results when several 300 kiloton nuclear weapons were detonated over Kazakhstan at various altitudes, disabling overhead and underground wires, causing spark-gap breakdowns, and creating power supply failures, all of which occurred 600 kilometers from the test site.[106] It should be noted that the majority of electronic equipment in the 1960s was powered by vacuum tube technology, which are less vulnerable to EMP events when compared to modern electrical systems.[107] This could indicate that, while there are numerous benefits of the advancement of microchip and wireless technology, our modern electrical and grid systems may be at an even greater risk of electromagnetic events.

EMP events are defined in several ways, but experts most agree that EMPs are considered to be short bursts of electromagnetic energy that can be spread throughout a range of frequencies that are the result of man-made or natural causes.[108] According to the Joint Chiefs of Staff Publication 1–02, an EMP is defined as "a strong burst of electromagnetic radiation caused by a nuclear explosion, energy weapon, or by natural phenomenon, that may couple with electrical or electronic systems to produce damaging current and voltage surges."[109] From a homeland security perspective, EMPs are classified as low probability-high consequence scenarios that create "hard problems" for policy makers and emergency preparedness planners.[110] While these definitions provide a good start, they do not entirely describe how EMP events interact with electrical systems or explain the components that are associated with an EMP event which consist of the E1, E2, and E3 pulses, all of which interact

[105] Foster Jr. et al., 4.

[106] Foster Jr. et al., 4.

[107] Electric Infrastructure Security Council, "USSR Nuclear EMP Upper Atmosphere Kazakhstan Test 184."

[108] Weiss and Weiss, "An Assessment of Threats to the American Power Grid," 4.

[109] "DOD Dictionary of Military and Associated Terms," September 13, 2021, Department of Defense, 2021, https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/dictionary.pdf.

[110] Department of Homeland Security, *Strategy for Protecting and Preparing the Homeland Against Threats of Electromagnetic Pulse and Geomagnetic Disturbances*, 10.

and affect electrical systems in different ways.[111] This section will focus on a high altitude EMP scenario created from a nuclear device detonated at 30 kilometers above ground level and explain the various aspects that are associated with such an event.

The E1 pulse, commonly 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.[112] 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.[113] 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.[114] Put another way, the E1 pulse travels so quickly and with so much voltage, standard surge protectors offer almost no protection against its effects, which puts most modern electrical devices at risk of being disabled by the initial pulse of an EMP event. In addition, depending on the height of burst, the E1 pulse can occur simultaneously over very large geographic areas, which can create large-scale regional power blackouts.[115] The E1 pulse has the potential to impact large power substations by creating high voltage which in turn will cause permanent damage to entire power systems, connected components, and large parts of the power grid.[116] Government agencies, such as the Department of Energy's Sandia

[111] Mao Congguang et al., "Early-Time High-Altitude Electromagnetic Pulse Environment (E1) Simulation with a Bicone-Cage Antenna," *China Communications* 10, no. 7 (2013): 12–18, https://doi.org/10.1109/CC.2013.6570795.

[112] Congguang et al., 12.

[113] 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 & Compalbility (INCEMIC)* (Bengaluru, India: IEEE, 2018), 1–4, https://doi.org/10.1109/INCEMIC.2018.8704567.

[114] Craig R. Lawton, *Sandia's Research in Electric Grid EMP Resilience*, ERPI 2018 EMP Resilient Grid Workshop (Albuquerque, NM: Sandia National Labs, 2018), 14, https://www.osti.gov/servlets/purl/1512391.

[115] Foster Jr. et al., *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack*, 30.

[116] Rodrigo Elias Llanes et al., *Early-Time (E1) High-Altitude Electromagnetic Pulse Effects on Transient Voltage Surge Suppressors*, SAND2020-11145-694100 (Albuquerque, NM: Sandia National Labs, 2020), 14, https://www.osti.gov/servlets/purl/1769004.

National Lab have worked with various educational institutions in an attempt to mitigate the effects of the E1 pulse but have proved to be unable to stop the E1 pulse from affecting large substations in simulated EMP environments.[117] The mitigation of the E1 pulse to large power systems remains a challenge because it takes place nanoseconds after a high altitude nuclear EMP event, meaning such events have the potential to create long-term effects on modern electrical systems.[118]

The E2 pulse, referred to as the intermediate pulse, of an EMP event takes place milliseconds after a high altitude nuclear EMP event and immediately follows the E1 pulse.[119] The E2 pulse is comparable in waveform and strength as lighting strikes, which makes it the easiest to protect against, but has the potential to put thousands of volts per kilometer and can cause significant amounts of damage to electrical systems, especially when it occurs immediately after the already disabling effects E1 pulse.[120] The most damaging effect of the E2 pulse is its ability to destroy protective and control features of most modern electronics which compounds the damage that already occurred by the E1 pulse.[121]

The E3 pulse, which is referred to as the long-term pulse, has significantly different characteristics from the E1 and E2 pulse as it can last seconds to minutes after the EMP event and creates power surges of tens of volts per kilometer.[122] The E3 pulse also differs in that it induces electrical fields which then produces GICs, which have the same effect that a GMD creates from naturally occurring solar storm events.[123] Powerlines can potentially carry the GICs produced from the E3 pulse to massive transformer stations, resulting in significant

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[117] Llanes et al., 50.

[118] 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.

[119] Kim and Jeong, 1.

[120] 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.

[121] Bontea, 13.

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

[123] Kim and Jeong, 2.

damage that could cause widespread power outages and greatly impede any recovery of the electrical systems and grids.[124] 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, depending on the height of burst, the effects of the EMP can cover large geographical areas as Figure 4 depicts.

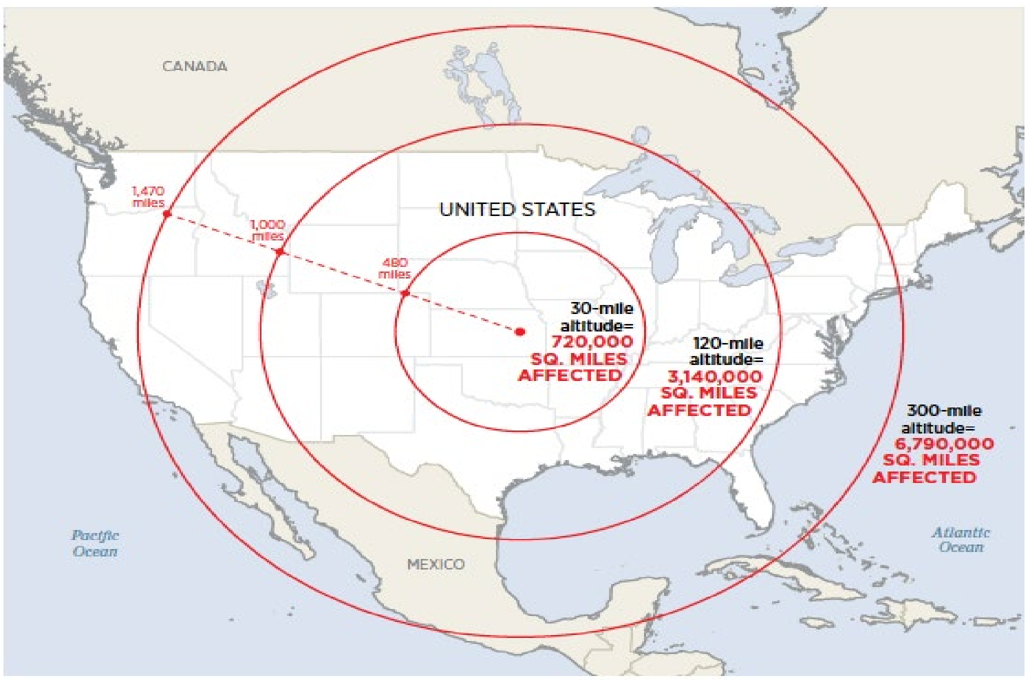

Figure 4. Depiction of potential damage from an EMP based on altitude of detonation[125]

EMP events have the potential to place enormous stress on U.S. electrical infrastructure. Because EMP events create three distinct and damaging waveforms, mitigation requires a significant number of resources. A combination of shieling, grounding, filter, and testing is required to ensure that electronic equipment will function

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124 Kim and Jeong, 2.

125 Michaela Dodge et al., "The Danger of EMP Requires Innovative and Strategic Action," *The Heritage Foundation*, no. 3299 (April 4, 2018): 5.

through the waveforms of an EMP event.[126] Unlike GMDs, which only damage large transformers though powerlines, EMP events have the potential to destroy transformers and various electronics; unfortunately, EMP modeling has not been able to fully anticipate how modern technology will react to a weaponized EMP attack.[127] The danger of EMP events is the potential for large-scale electrical grid failure and the failure of other smaller electronics that will potentially result in cascading damage to other parts of American society, which will have little to no warning of an impending EMP event.

A historical example of how EMPs can affect electrical systems is the USSR nuclear tests from the early 1960s. In 1962 the Soviet Union conducted the K test by detonating three 300 kiloton nuclear devices at altitudes of 150 km, 300 km, and 80 km.[128] The purpose of the K tests was to gather data for high-altitude nuclear detonations for Soviet anti-ballistic missile defense systems and the effects on electrical equipment associated with Soviet air defense networks.[129] While the results of these tests have been difficult to acquire, several sources have confirmed that there was significant damage to the electrical infrastructure as both Soviet radars and communication systems were damaged, some of which were between 600–1000 km away from the test site as the results from all three waveforms of an EMP event from a nuclear detonation.[130] As Figure 5 reveals, civilian infrastructure, including powerlines, power generator stations, and other electronic equipment, all of which was 600 km away from the test site, also suffered damage.[131]

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126 Electric Infrastructure Security Council, "USSR Nuclear EMP Upper Atmosphere Kazakhstan Test 184."

127 Electric Infrastructure Security Council.

128 Anatoly Zak, "THE 'K' PROJECT: Soviet Nuclear Tests In Space," *The Nonproliferation Review* 13, no. 1 (March 1, 2006): 143, https://doi.org/10.1080/10736700600861418.

129 Zak, 144.

130 Electric Infrastructure Security Council, "USSR Nuclear EMP Upper Atmosphere Kazakhstan Test 184."

131 Electric Infrastructure Security Council.

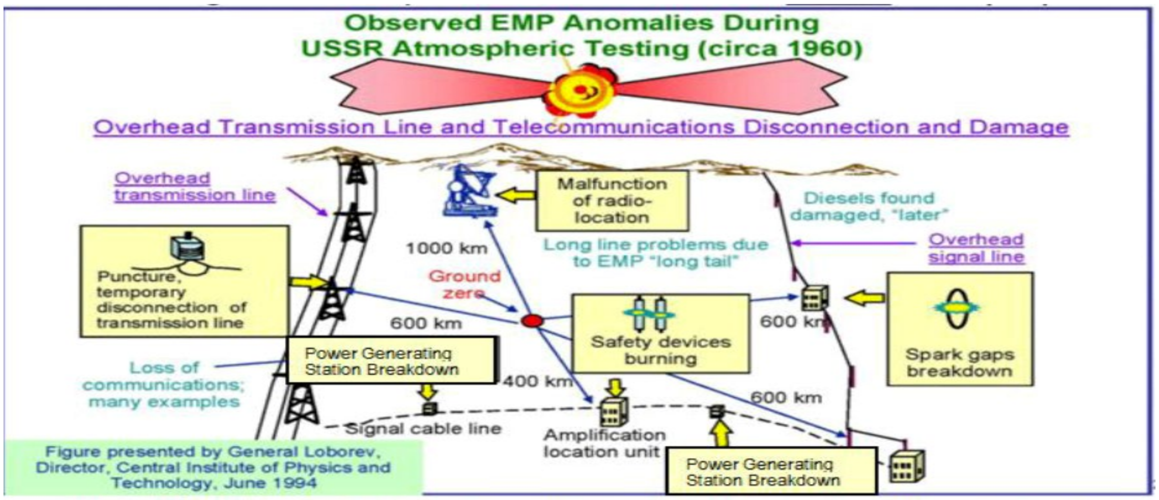

Figure 5. Description of the effects on electrical infrastructure after the 1962 Soviet atmospheric nuclear tests[132]

C. COMPARING GMD AND EMP IMPACTS, MANAGEMENT, AND MITIGATIONS

EMP/GMD events have serious consequences for government agencies, utility operators, and the civilian population as they both have the potential to create catastrophic effects on electronic devices and infrastructure. Even though EMPs and GMDs share some similarities in their potential for catastrophic impacts on critical infrastructure, they have important distinctions for system protection and resilience.

Key differences between EMPs and GMDs include the size and scope of their impacts on infrastructure systems. Figure 6 illustrates several key differences between EMP and GMD event impacts[133] and Figure 7 summarizes the potential effects that different electromagnetic events may have on critical infrastructure systems. While EMPs can inflict direct permanent effects on all types of systems and infrastructure, GMDs are expected to cause fewer damages and disruptions. This is due to the effects of E1 and E2 pulses associated with EMPs, but not GMDs. However, GMDs are likely to impact larger regions than EMPs, even if EMPs are caused by high-altitude nuclear detonation. This is

[132] Electric Infrastructure Security Council.

[133] Department of Energy, *U.S. Department of Energy Electromagnetic Pulse Resilience Action Plan*, 4.

based on the enormous size of CMDs recently measured by NASA. Thus, a single GMD can impact all vulnerable transformers across North America, where it is more difficult and less likely to have an EMP with similar large-scale effects without significant range and capability of nuclear weapons. Taken together, EMPs are likely to destroy all electrical infrastructure within their impact radius, but the radius is smaller than a GMD. In contrast, GMDs are less destructive, but are expected to impact much wider regions.

Attribute	EMP	GMD
Cause	Adversarial threat	Natural hazard
Warning	Strategic: unknown Tactical: none to several minutes	Strategic: 18 to 72 hours Tactical: 20 to 45 minutes
Effects	*E1:* High peak field – quick rise time *E2:* Medium peak field *E3:* low peak field, but quicker rise time and higher field than for GMD (possibly 3 times higher)	No comparable E1 wave forms No comparable E2 wave forms *E3:* low peak field – fluctuating magnitude and direction
Duration	*E1:* less than a 1 microsecond *E2:* less than 10 millisecond *E3 Blast:* ~10 seconds *E3 Heave:* ~1 – 2 minutes	No comparable E1 wave forms No comparable E2 wave forms *E3:* hours
Equipment at Risk	*E1:* telecommunications, electronics and control systems, relays, lightning arrestors *E2:* lightning: power lines and tower structures – "flashover", telecommunications, electronics, controls systems, transformers. *E3:* transformers and protective relays – long run transmission and communication - generator step-up transformers	*E3:* transformers and protective relays – long-haul transmission and communications – generator step-up transformers
Footprint	Regional to continental depending on height of burst	Regional to worldwide, depending upon magnitude
Geographic Variability	Can maximize coverage for E1 or E3 *E3:* intensity increases at the lower latitudes and as distance from ground zero is decreased or as yield is increased	*E3:* intensity increases near large bodies of water and generally at higher latitudes although events have been seen in southern latitudes

Figure 6. Key differences between EMP and GMD events[134]

[134] Department of Eneprgy, 4.

Equipment At Risk	EMP (Nuclear)	GMD (Solar Storm)
Generator Stations	Direct Permanent Effect	Direct Effect Uncertain
SCADA/Industrial Controls	Direct Permanent Effect	Direct Permanent Effect
Utility Control Centers	Direct Permanent Effect	Direct Permanent Effect
Telecommunications, to include cellphones	Direct Permanent Effect	Direct Permanent Effect
Internet	Direct Permanent Effect	Direct Permanent Effect
Radio Emergency Communications	Direct Permanent Effect	Temporary Effect (.5-36 hours) assuming backup power
GPS	Direct Permanent Effect	Temporary Effect (.5-36 hours) assuming backup power
Transportation	Direct Permanent Effect	Cascading effects (if no backup power is available)
Water	Direct Permanent Effect	Cascading effects (if no backup power is available)

Figure 7. Chart comparing the effects of EMPs and GMDs on various critical infrastructure systems[135]

EMPs and GMDs also differ in how organizations can respond to them if and when they happen. To provide a simple example, we compare EMP and GMDs to more familiar natural disasters that occur more frequently. A GMD is like a large-scale hurricane, with the caveat that its effects are restricted to electrical infrastructure. Like hurricanes, GMDs travel slowly from the source of their origin, in this case the sun, and eventually make contact with the Earth's atmosphere but give its intended target some early warning.[136] Existing satellite infrastructure and monitoring systems are capable to detect GMDs 15–90 hours before they impact Earth.[137] This means government and private organizations may have the time to prepare electrical systems to reduce impacts.

On the other hand, EMP events are more like large-scale earthquakes, as they often come with little to no warning and will leave the majority of the population surprised and unprepared. The only warning of an EMP would likely come from a missile defense system, suggesting that government and private entities may only have minutes to prepare electrical systems and reduce impacts. In both cases, the physical damage is limited to electrical systems and devices, yet their potential catastrophic effects on electrical

[135] Wang et al., "Power Grid Resilience to Electromagnetic Pulse (EMP) Disturbances," 3.

[136] Department of Homeland Security, *Federal Operating Concept for Impending Space Weather Events*, 1.

[137] Department of Homeland Security, 2.

infrastructure could create serious issues to national security and the civilian population due to blackouts and prolonged cascades.

Finally, the impacts of EMP and GMD events can be mitigated in different ways, since they are more or less responsive to different national and international policies and system protections. EMPs are associated with nuclear weapons, so the potential impacts of EMPs can be attenuated through international policies for deterrence, control, and use of nuclear weapons. More effective weapons control policies and coordination among and within nations can have an appreciable effect on EMP size and scope. In contrast, GMDs being naturally occurring events are not responsive to any form of treaty or coordination. However, GMDs are less destructive, and their effects like GICs are better modeled and understood. Thus, national and international policies for power system hardening and protection as well as solar monitoring and CME prediction may improve resilience to GMDs.

D. CONCLUSION

This chapter serves as a body of knowledge that provides background information on EMP/GMD events that is important to understand for Chapter III. In Chapter III, two thought experiments will be used in order to determine what would happen if these events occurred today and what actions could be taken from government agencies and the civilian population. While there is no real way to absolutely predict how the American government or the civilian population would react, current federal standard operating procedures and historical information on past natural disasters will be used as a guideline to generally forecast what actions would be taken if an EMP or GMD occurred in the near future.

III. THOUGHT EXPERIMENTS: HOW PAST EVENTS COULD AFFECT PRESENT DAY INFRASTRUCTURE

This chapter employs two thought experiments to forecast how past EMP/GMD events would affect present-day electrical and electronic infrastructure and modern society. As shown in Chapter II, there are well-known differences between GMD and EMP events, as well as known impacts, responses, and mitigations. Despite various modeling efforts to replicate how electromagnetic events occur (GMDs in particular), there is still limited scientific knowledge for how these events will affect systems in the future because society has observed so few electromagnetic events on Earth.[138] In particular, there is limited discussion of the decision-making contexts generated by each event that eventually dictate their realized impacts on society, rather than their modeled impacts on infrastructure. This limits government agencies and infrastructure utilities from making more effective plans and practices for future disasters.

Thought experiments offer a means to develop realistic, yet fictious scenarios that reveal decision-making contexts, societal impacts, and other issues relevant for GMD and EMP resilience. Here, we develop thought experiments as fictional events that occur in the near future, incorporate present day infrastructure capabilities, and consider known historical societal trends. Specifically, a mental-model will be utilized to forecast the effects of present-day capabilities paired with government agencies' shortfalls, U.S. electrical infrastructure, and the civilian population.[139] These thought experiments can reveal expected response by federal agencies, infrastructure utilities, and general publics. They also describe cascading effects on modern society and homeland security by analyzing built scenarios based on historical and real-world data. Developing scenarios that describe these effects can inform current system resilience by revealing how well governments, utilities, and publics can sense, anticipate, adapt to, and learn from GMDs

[138] Edward J. Oughton et al., "A Risk Assessment Framework for the Socioeconomic Impacts of Electricity Transmission Infrastructure Failure Due to Space Weather: An Application to the United Kingdom," *Risk Analysis* 39, no. 5 (May 2019): 1022, https://doi.org/10.1111/risa.13229.

[139] Brown and Fehige, "Thought Experiments."

and EMPs. Moreover, these scenarios can reveal shortfalls in system robustness, rebound, extensibility, and adaptability capacities that must be addressed.

This chapter models two electromagnetic events that occurred in the past, the 1859 Carrington GMD event and the 1962 USSR nuclear EMP test. Each thought experiment includes several subsections that examine how homeland security agencies, electrical infrastructure, and the civilian population are each effected by electromagnetic events. Based on the results of the case studies, there were significant vulnerabilities to EMP/GMD events that could have serious implications to national security and the civilian population.

A. THOUGHT EXPERIMENT 1: MODERN-DAY CARRINGTON EVENT

This first thought experiment develops a future, fictional scenario where a Carrington-level GMD event occurred in the near future. The Carrington Event was the most powerful GMD to have been recorded in modern history and is estimated to have reached Earth 17.6 hours after the initial solar flare that took place on the surface of the sun.[140] Richard Carrington first observed this flare though his telescope while observing the sun and noticed two bright spots moving along the sun's surface and estimated those spots to have been roughly the size of Earth.[141] Several astronomers and scientists throughout the world observed what followed: unusual Aurora Borealis displays at Southern latitudes in places such as Cuba and catastrophic destruction of telegraph systems in North America.[142] The amount of damage from the Carrington event was estimated to be between $200,000-300,000 in 1859 U.S dollars.[143] This section will review the current state of today's electrical infrastructure, and provide a hypothetical scenario that will depict how modern systems might be impacted by a Carrington size GMD.

Carrington-level GMD events are difficult to predict even though there has been significant research and modeling of such an event. Some studies have predicted that there

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140 Robert D. Loper, "Carrington-Class Events as a Great Filter for Electronic Civilizations in the Drake Equation," *Publications of the Astronomical Society of the Pacific* 131, no. 998 (March 2019): 2, https://doi.org/10.1088/1538-3873/ab028e.

141 Giegengack, "The Carrington Coronal Mass Ejection of 1859," 3.

142 Giegengack, 3.

143 Giegengack, 4.

is a 28% chance of a large-scale GMD event occurring each eleven-year solar cycle (at least 1 event in 98 years with 95% confidence), while others predict there is a 10.3% chance of a Carrington-level GMD occurring per decade (at least 1 event in 275 years with 95% confidence).[144] Regardless of how often these events occur, it is clear that at some point, Earth will experience a large-scale GMD event that has serious implications for both the national security of the United States and that of other nations.

1. Federal Response Capacities Pre-Event

GMD events are unique in that modern technology now has the capability to identify and predict solar events such as CMEs that have the potential to become GMD events. The NOAA's Space Weather Prediction Center has the ability to provide between a 15-to-90-hour early warning before a potential GMD interacts with the Earth's atmosphere.[145] Tracking and identifying a GMD event, while important, is only the beginning of the problem-set. The next step would be to disseminate that information to DHS, who would then need to notify power utility providers and the public of the ramifications of an impending GMD event, which is categorized as Elevated Threat (Phase 1B), according to the Federal Operating Concept for Space Weather Events.[146] The Federal Operating Concept for Space Weather events is the standard operating procedure that DHS uses to synchronize and execute all mitigation efforts in response to a GMD event. This operating concept gives detailed instructions for each agency within DHS and provides a step-by-step guide for all actions that need to be taken at each phase. A critical factor to consider would be the time of day that DHS disseminates the GMD warning to power utility providers as it would be easier to coordinate massive power adjustments during the night versus during the day when most of the public is at work.

[144] Oughton et al., "A Risk Assessment Framework for the Socioeconomic Impacts of Electricity Transmission Infrastructure Failure Due to Space Weather," 1024.

[145] Department of Homeland Security, *Federal Operating Concept for Impending Space Weather Events*, 3.

[146] Department of Homeland Security, 3.

2. U.S. Federal Response

The following describes a fictitious, but realistic response to a Carrington-level GMD event taking place 4 years in the future. On January 23rd, 2025, the NOAA Space Weather Prediction Center (SWPC) identifies a significant CME event on the Sun's surface. As the NOAA SWPC continues to observe the CME, it determines that a G5 GMD has occurred and will interact with the Earth's atmosphere in 15 hours, which triggers the DHS to enter phase 1B of the Federal Operating Concept for Space Weather Events.[147] Immediately, DHS's National Operations Center (NOC) notifies all internal departments, including FEMA, and external federal agencies, specifically the DOE and NERC.

While there is no specific timeline listed in the Federal Operating Concept, all government agencies will assess their expected vulnerability to the incoming GMD and attempt to mitigate these vulnerabilities as soon as possible.[148] FEMA issues an initial operation order to all Regional Response Coordination Centers, State Offices of Preparedness and local agencies and continue to monitor all aspects of the status of national preparedness from FEMA's National Watch Center (NWC).[149]

The GMD is confirmed by NOAA with great confidence that it will interact with Earth's atmosphere, the SWPC transition to Phase 1C, the credible phase, and will issue a Geomagnetic Disturbance Warning as all other agencies continue to prepare and monitor the situation.[150] During this time, NASA, NOAA, and DHS will have a clear understanding of what areas the GMD will affect, as most solar storms have historically impacted areas of the Earth along the 50-degree northing that is depicted in Figure 8.[151]

147 Department of Homeland Security, 11.

148 Department of Homeland Security, 12.

149 Department of Homeland Security, 12.

150 Department of Homeland Security, 12.

151 Lewandowski, "Protection of the Smart City against CME," 6.

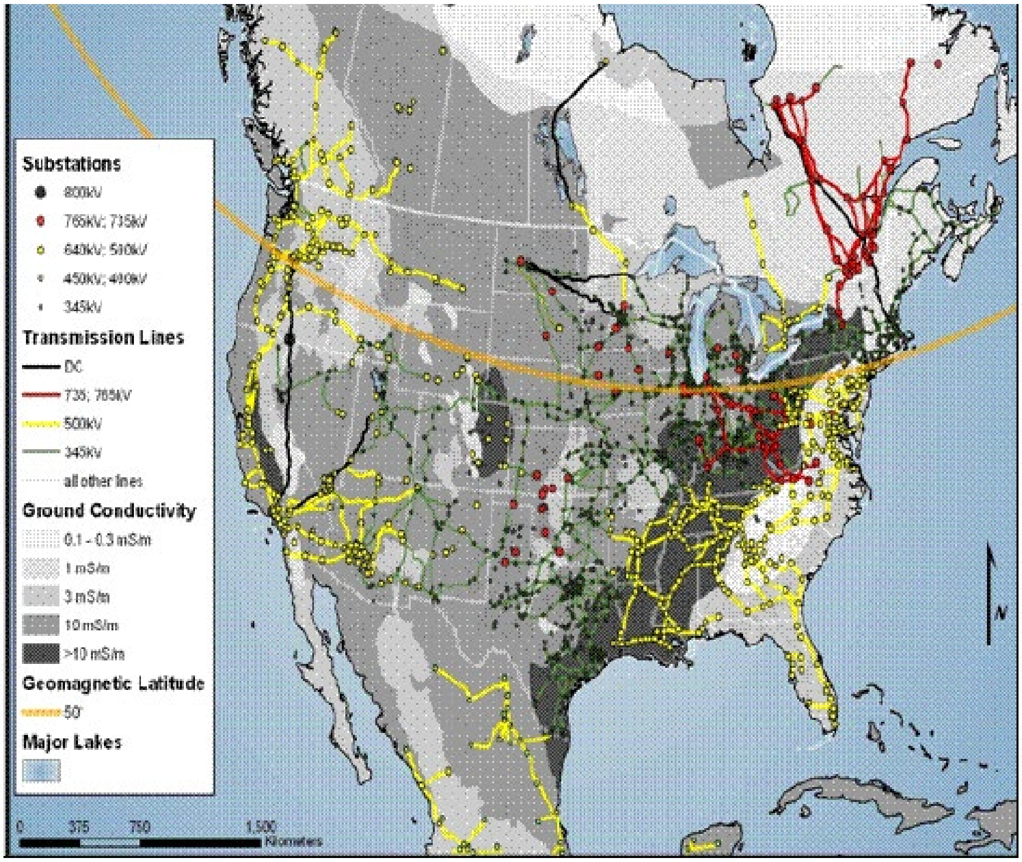

Figure 8. Map depicting key transformer locations and the standard geomagnetic latitude[152]

3. Power Industry Response

Upon notification of an impending GMD event, the highest levels of government, along with the DOE, NERC, and power utility councils, will be forced to make significant decisions that will incur extraordinary impacts to large portions of the population to protect the electrical grid and key critical infrastructure within 12–15 hours. Before GICs start to impact the electrical grid by way of transformer failures, policymakers will have to decide to shut down certain parts of the grid and rely on other parts that are better protected against GMD events or have GIC blocking devices installed.

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 and

[152] Lewandowski, 6.

NERC to immediately disseminate orders and plans to the NERC interconnections, which include the Western Interconnection, Electric Reliability Council of Texas (ERCOT) Interconnection, and Eastern Interconnection who then manage the individual utility operators to prepare the grid for the impending GIC effects. Figure 9 displays how the NERC interconnections are arrayed and how much coordination is needed for massive changes to the grid system.[153] Once power utilities are ready to implement the decided course of action, the FEMA NWC initiates emergency communication messages to the civilian population and local jurisdictions on what areas of the country should expect to lose power. Power utility companies prepare strategically located reserve transformers to replace any transformers that are critically damaged during the GMD event.

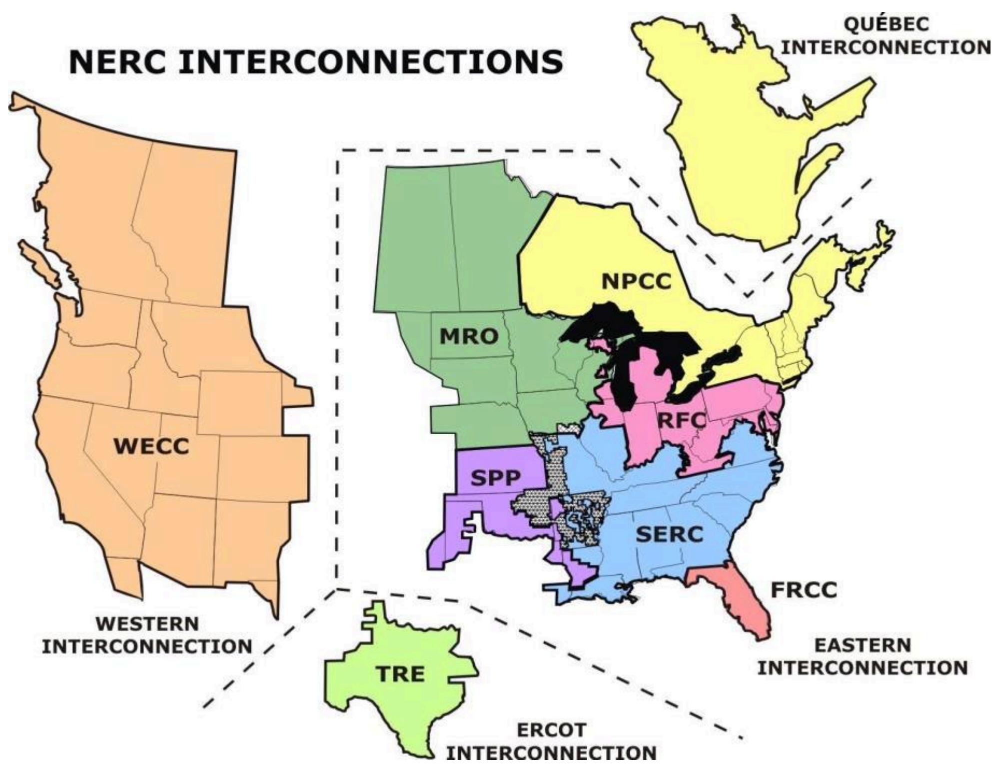

Figure 9. Geographic depiction of NERC Interconnections[154]

[153] Greene, "Nuclear Power," 7.

[154] Greene, 8.

4. Effects on the Power Grid

While the U.S. national grid has mitigations already put in place against GMD events, the standards of protection that NERC regulates are potentially too low to protect against a Carrington-level GMD event.[155] GIC blockers are viewed as a method to mitigate against GMD but it is unknown how many major transformers have these devices installed.[156] Various virtual models have attempted to determine how large-scale GMD event would impact the entire U.S. grid system; most predict the catastrophic failure of certain parts of the overall grid system.[157] Additionally, the NERC standards for protection against electromagnetic events is 8 V/km, which is derived from the 1989 Canadian GMD event.[158] Despite NERC protection standards, a study from the Los Alamos National Laboratory estimated the intensity of a large scale GMD, such as the Carrington event, at ranges close to 13.6-16.6 V/Km, which has the potential to cause extensive damage to the grid despite mitigation measures already put in place.[159] Other strategies include shutting down the national grid before a GMD occurs but it is unknown if this would be an effective mitigation measure against GMDs and how long it would take to turn the grid back on. There remain significant gaps in understanding how large-scale GMDs would affect modern electrical systems and how to properly mitigate these dangers.[160]

As the GMD comes into the Earth's atmosphere, GICs create significant damage to the unprotected parts of the grid that cause cascading effects across the country. There will

[155] Weiss and Weiss, "An Assessment of Threats to the American Power Grid," 3.

[156] F. R. Faxvog et al., "Power Grid Protection against Geomagnetic Disturbances (GMD)," in *2013 IEEE Electrical Power & Energy Conference* (Fort Belvoir, VA: IEEE, 2013), 2, https://doi.org/10.1109/EPEC.2013.6802963.

[157] Brian Joseph Pierre et al., *Modeling Bulk Electric Grid Impacts from HEMP E1 and E3 Effects.*, SAND2021-0865 (Albuquerque, NM: Sandia National Lab, 2020), 37, https://doi.org/10.2172/1764794.

[158] North American Electric Reliability Corporation, *Benchmark Geomagnetic Disturbance Event Description*, NERC-2016-021 (Atlanta, GA: North American Electric Reliability Corporation, 2016), 6, https://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/Benchmark_GMD_Event_April21_2.pdf.

[159] Weiss and Weiss, "An Assessment of Threats to the American Power Grid," 3.

[160] Department of Energy, *Geomagnetic Disturbance Monitoring Approach and Implementation Strategies*, GDMAIS-2019 (Washington, D.C: Department of Energy, 2019), https://www.energy.gov/sites/prod/files/2019/06/f64/DOE_GMD_Monitoring_January2019_508v2.pdf.

most likely be a significant effort to protect major centers, which may have intermittent to reliable power, but many small communities may be without power due to the cascading effects of large-scale grid failure combined with a lack of resources and coordination.[161] It is also possible that some rural areas, which are not dependent on large EHV transforms, may experience fewer cascading effects than large population centers. Population centers that suffered permanent damage to transformers could be without power for weeks to months, depending on how fast a transformer could be delivered from a strategic storage location, if at all. Currently the DOE, NERC, and various power utility companies are unsure if lessening the power requirements or shutting off EHV transformers will mitigate the effects of GMD events on the national power grid as it is very hard to simulate such an event.[162] Modern transformers cost in excess of 1 million dollars and can take up to 18 months to manufacture and install under normal conditions, much less in a state of emergency.[163]

5. Effects on the U.S. Population and Interdependent Infrastructure Systems

In rural and small communities, the loss of power for days to weeks will have disastrous effects on everyday life. Hospitals would normally rely on uninterrupted power supply from backup generators, but as these assets are not hardened against GMD events, these generator assets would most likely be inoperable. Hospitals will need to triage patients and move them to facilities that have a reliable power supply but, in the long term, the surge of patients overwhelm the health care system and result in numerous fatalities as similar events from lesser natural disasters stressed hospital systems within seven days of

[161] 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), www.cisa.gov%2Fsites%2Fdefault%2Ffiles%2Fpublications%2FNIAC%2520Catastrophic%2520Power%2520Outage%2520Study_FINAL.

[162] Department of Energy, *Geomagnetic Disturbance Monitoring Approach and Implementation Strategies*, 13.

[163] Loper, "Carrington-Class Events as a Great Filter for Electronic Civilizations in the Drake Equation," 2.

losing power.[164] In addition, some of the more advanced healthcare systems may be damaged or degraded due to the GMD event.

Satellites in both low Earth Orbit and geosynchronous orbit will be degraded or damaged by the GMD's GICs which will create a loss of communications, GPS, banking, and other essential services.[165] Many ground-based fiber optic communications assets will also be degraded as the most power sources will be offline; this will also diminish other means of emergency systems such as radio broadcasts.[166] City and county services such as law enforcement and emergency services will struggle to respond to emergencies as communication and cellular towers will be degraded or without power in many regions as was shown in the aftermath of Hurricane Katrina were emergency services had no method of recharging hand held communication devices.[167]

The cascading effects will take a toll on large population centers that have a reliable source of power as large amounts of people may choose to migrate into areas that have stable electricity or other essential services.[168] For example, during Hurricane Katrina, over one million people fled New Orleans in an attempt to survive the after effects of the storm.[169] FEMA will attempt to set up areas with key supplies and shelter but due to the rapid timeline of the CME, could not deploy enough assets in the time allotted. The civilian population will suffer as basic services break down as most community preparedness guidelines only call for 72 hours' worth of essential supplies per family unit, which is

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164 Alison Gowans, "For Those with Medical Needs, Storm That Hit Cedar Rapids Turns Life-Threatening," The Gazette, August 14, 2020, https://www.thegazette.com/news/for-those-with-medical-needs-storm-that-hit-cedar-rapids-turns-life-threatening/.

165 Loper, "Carrington-Class Events as a Great Filter for Electronic Civilizations in the Drake Equation," 4.

166 Loper, 4.

167 Benjamin Sims, "'The Day after the Hurricane': Infrastructure, Order, and the New Orleans Police Department's Response to Hurricane Katrina," *Social Studies of Science* 37, no. 1 (2007): 113, https://doi.org/10.1177/0306312706069432.

168 The President's National Infrastructure Advisory Council, *Surviving a Catastrophic Power Outage, How to Strengthen the Capabilities of the Nation*, 12.

169 Tom Dart, "'New Orleans West': Houston Is Home for Many Evacuees 10 Years after Katrina," *The Guardian*, August 25, 2015, sec. U.S. news, https://www.theguardian.com/us-news/2015/aug/25/new-orleans-west-houston-hurricane-katrina.

nowhere near sufficient in a post-GMD environment.[170] In addition, due to the early warning given to the civilian population, retail and grocery stores could experience significant supply issues as many people will 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.[171]

Coordination of military forces, both active duty and reserve forces, will be challenging as many areas will have no or intermittent power and limited coordination was made prior to the GMD. These factors would disrupt key power generation assets which may make various communication platforms unreliable. Deployment of military forces will most likely be slow and cumbersome due to the incredibly fast timeline of the GMD event. Depending on location, some military facilities may suffer from power loss, especially if they are not equipped with back-up generators, making coordination and deployment extremely challenging. However, military personnel will be extremely vital in order to keep order in large population centers as local emergency services will either be overwhelmed or non-existent.

Telecommunication, GPS, and other satellite infrastructure would also be adversely affected by a large-scale GMD.[172] Cell phones and other modern communication devices would unable to be utilized in affected areas because most cell phone networks would be disabled due to the GMD's effects on the atmosphere. GPS, to include the Wide Area Augmentation System used for commercial aviation, would also be disabled.[173] These factors, combined with the potential large scale power loss, would be catastrophic for modern society. Until GPS and telecommunications is restored, most aviation assets, financial institutions, and emergency services would be severely degraded or non-existent.

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170 The President's National Infrastructure Advisory Council, *Surviving a Catastrophic Power Outage, How to Strenghen the Capabilities of the Nation*, 13.

171 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.

172 Pete Riley et al., "Extreme Space Weather Events: From Cradle to Grave," *Space Science Reviews* 214, no. 1 (2018): 6, https://doi.org/10.1007/s11214-017-0456-3.

173 Riley et al., 6.

6. Thought Experiment 1 Summary

As this scenario demonstrates, there are various hazards to government agencies and the civilian population in the post-GMD environment. We expect early warning of the event and activation of existing federal and utility plans to protect systems. Even with early warning, a Carrington-type GMD event would have disastrous effects on American society, the likes of which would be completely novel to present-day generations. The strength of a Carrington-type event will exceed existing protections on the power grid, leading to large-scale infrastructure failure even with 12–15 hours of preparation time. Other vulnerable and interdependent infrastructure systems will also be impacted. Many satellites and communications technologies will be lost. This can be exacerbated with new technologies, such as 5G communications, that have enormous benefits but also puts systems at great risk of solar events. Overall, we should expect certain regions that are less vulnerable to EHV transformer failures, loss of communications, and loss of related systems (e.g., internet) to be less impacted. We expect regions with more dependency on these technologies and in more populated regions to be more impacted.

There are several possibilities for both governmental response and to civilian populations as to what would actually occur in a post GMD environment. Historically, natural disasters often bring communities together through shared hardship or experience.[174] However, power blackouts in particular take away the "technical unconscious" or infrastructure that make everyday life possible for modern society and often results in civil unrest, increased crime, and severe economic consequences.[175] The physical infrastructure of modern society would be undamaged, but the usage of many services that are common today would be unavailable, which, much like electrical infrastructure, would have cascading effects on society at large. Coordination of emergency and military response to support communities will be hampered from the loss of power and

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[174] Keren Segal, Jonathan Jong, and Jamin Halberstadt, "The Fusing Power of Natural Disasters: An Experimental Study," *Self and Identity* 17, no. 5 (September 3, 2018): 574, https://doi.org/10.1080/15298868.2018.1458645.

[175] Hugh Byrd and Steve Matthewman, "Exergy and the City: The Technology and Sociology of Power (Failure)," *The Journal of Urban Technology* 21, no. 3 (June 2014): 87, https://doi.org/10.1080/10630732.2014.940706.

communications technologies. The impacts for urban communities may be immediate and large due to their distinct vulnerability to blackouts. Moreover, the impacts to rural and isolated communities may last weeks to months, exacerbating effects.

B. THOUGHT EXPERIMENT 2: ADVERSARIAL EMP ATTACK

The second thought experiment involves a hypothetical EMP attack on the United States. Weaponized high altitude EMP attacks are high-impact/low-probability events that have significant implications on homeland security. Analysis of the test data from the 1962 Soviet Nuclear EMP test suggests that a high altitude EMP attack has the potential to cause catastrophic damage to the national security of the United States.[176]

1. Federal Response Capacities Pre-Event

Unlike GMD events, there may not be several hours or days to prepare before any EMP attack takes place. Based on modern missile capabilities, the Department of Defense may only have a 30-minute window to react before the effects of an EMP attack begins.[177] In addition to the lack of early warning, EMPs can have a more destructive effect than GMD events on electrical infrastructure due to the increased damage from all three pulses that occur as a result of EMP weapons. As of 2018, there were no devices that existed to mitigate the effects of the E1 pulse on major transformers, much less the cascading effects of the following E2 and E3 pules, which creates a serious vulnerability to the national grid system.[178]

2. U.S. Federal Response

Similar to the first thought experiment, this thought experiment will develop a fictional scenario which depicts possible outcomes of an EMP attack on the United States 3 years in the future. On November 12, 2024, a submarine-launched hypersonic ballistic missile with a 300-kiloton warhead is launched from an undisclosed location in the North

[176] Electric Infrastructure Security Council, "USSR Nuclear EMP Upper Atmosphere Kazakhstan Test 184."

[177] Dodge et al., "The Danger of EMP Requires Innovative and Strategic Action," 10.

[178] Lawton, *Sandia Research in EMP Resilience*, 14.

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, to 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.[179]

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 that has not been experienced in generations. 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.

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. Common 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.

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

Responses from active-duty military forces throughout the country will be degraded because most military facilities are dependent on the local community for power and will most likely be in the same situation as the local community the base resides in.[180] Like the GMD scenario, both active and reserve military forces will be essential to support law enforcement and other emergency services as local and regional agencies will be overwhelmed with the post-EMP environment.

3. Power Industry Response

A high-altitude EMP attack has the potential to cause significant damage to the national grid system and the ensuing cascading effects that take place in the post-EMP environment. While FERC standard for electromagnetic protection is regulated at 8 V/km, a weaponized EMP from a nuclear warhead would create conditions where over thousands of V/km would occur during the E1 and E2 pules and up to 85 V/km during the E3 pulse, indicating that the U.S. power grid exhibits extreme vulnerabilities to an EMP attack.[181] The increased voltage in the atmosphere, paired with the little to no warning to grid utility management organizations would have disastrous effects on the grid system, which would then jeopardize other sectors of critical infrastructure and create systemic issues for American society. 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.

4. Effects on the Power Grid

A single high-altitude EMP blast has the potential to permanently disable all electrical systems, to include high voltage generators and exposed SCADA systems, that are within the blast radius.[182] This was demonstrated during the EMP Commission's unclassified report as various electrical systems failed to function when exposed to

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[180] Cynthia E. Ayers and Ken Chrosniak, "Terminal Blackout: Critical Electric Infrastructure Vulnerabilities and Civil-Military Resiliency," in *Army War College (U.S.). Center for Strategic Leadership* (Fort Leavenworth, KS: Army War College (U.S.). Center for Strategic Leadership, 2013), 5, https://www.hsdl.org/?abstract&did=.

[181] Weiss and Weiss, "An Assessment of Threats to the American Power Grid," 5.

[182] Weiss and Weiss, 5.

simulated EMP energy.[183] In short, the power grid could be expected to experience long-term catastrophic failures. Efforts to provide any type of recovery to EMP affected areas would have to come from agencies and utilities that were outside the blast radius, which could take years to fully bring these areas to pre-event conditions.[184]

5. Effects on the Civilian Population and Interdependent Infrastructure Systems

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 safeguard critical infrastructure and create hardened federal communication networks in order to maintain communications.[185] However, these reports to 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.[186] In addition, when only 2 percent of the U.S. population currently works in agriculture, where there is a massive reliance on electric automated services, food security will be a serious concern for local government and individual family units as the ability to mass produce and distribute food will be significantly degraded until power is restored and food shortages will occur shortly after the onset of the event.[187]

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 assets will be

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183 Weiss and Weiss, 5.

184 Weiss and Weiss, 2.

185 "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.

186 Stuckenberg, Woolsey, and DeMaio, *Electromagnetic Defense Task Force 2.0*, 109.

187 Stuckenberg, Woolsey, and DeMaio, 109.

unable to function. Wastewater and sewerage system failures will produce unsanitary conditions in the areas that are within the EMP blast radius, and make many areas uninhabitable for the civilian population as clean water will be harder to acquire as blackouts continue.[188] Life as most Americans know it will be forever changed as recovery from a weaponized EMP attack is hard to predict, some sources estimate recovery taking months to years as some vital electronic assets such as transformers can take several months to construct under normal conditions.[189]

6. Thought Experiment 2 Summary

In the EMP scenario, there was under an hour warning for elements of the Department of Defense and no warning to the civilian population. Due to the lack of warning time, there was no effort made to protect key parts of our critical infrastructure, specifically the electrical grid. Once the EMP attack took place, the overwhelming increase in atmospheric voltage would cause the power grid to fail in many large geographic areas. This caused the cascading effects to other crucial infrastructure sectors.

This event showcased how the absence of early warning contributed greatly to the lack of response that was available to government agencies. One key issue that is relevant to both events is the preparedness of individual families or residents that reside in a particular area. As previously mentioned, most preparedness campaigns call for enough supplies to cover a 72-hour period, which is simply not enough to be self-sufficient in a post EMP/GMD environment.[190] Some states have started to recommend that families prepare enough provisions for 14 days and are cultivating a culture of preparedness that resembles the "Civil Defense" mindset from the Cold War, which could potentially put less stress on local, state, and federal agencies when dealing with the effect of a EMP/GMD event.[191]

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188 Foster Jr. et al., *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack*, 10.

189 Foster Jr. et al., 6.

190 The President's National Infrastructure Advisory Council, *Surviving a Catastrophic Power Outage, How to Strengthen the Capabilities of the Nation*, 13.

191 The President's National Infrastructure Advisory Council, 13.

C. CONCLUSION

There have been various predictions and outcomes predicted as to what would actually happen if a GMD or EMP event occurred to the United States, but unfortunately, until such an event occurs, it is impossible to truly predict and prepare for such an unfamiliar event. However, the two thought experiments demonstrate possible outcomes that may transpire when electromagnetic events occur in present day or near future. We find differences among the thought experiments that determine whether government agencies, electrical systems, and publics may or may not be resilient the effects of electromagnetic events.

With the Carrington thought experiment, there was an ability to provide some sense of early warning but catastrophic failures did occur as the atmospheric voltage was much higher than present-day electrical infrastructure is designed to withstand. One critical factor that separated the severity between a GMD scenario and an EMP scenario was the ability to provide early warning. The EMP thought experiment showcased how a surprise attack could have devastating effects on our electrical infrastructure as there was no time to react or anticipate the event. Both thought experiments also demonstrated that when large geographic areas lose power simultaneously, cascading effects that can be observed in other critical infrastructure systems and society in general.

The capabilities and shortfalls of modern critical infrastructure systems provide a basis for how these systems would react to electromagnetic events, with emphasis on response to atmospheric voltage and interaction to electrical systems. It appears that an EMP/GMD event has the potential to cause serious damage to the electrical grid and create cascading effects to both critical infrastructure and modern society.

The next chapters will provide more detailed analysis of each thought experiment using the SAAL framework and the Woods resilience framework. Using these methods of analysis, this thesis will attempt to better understand what mitigation efforts can be taken and make recommendations to create more resilient systems that could mitigate the effects of EMP/GMD events to critical infrastructure and society.

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IV. SAAL ANALYSIS OF EMP/GMD SCENARIOS

In order to improve the resilience of critical infrastructure systems to the effects of electromagnetic events, we must first understand how human decision making and technology interact. In the context of high impact/low probability events that have significant impacts to national security, the assessment of human behavior should be an integral part of making our critical infrastructure and society more resilient.[192] This chapter analyzes the relationship between human behavior and technology using the SAAL approach, which was described in Chapter I. Applying the SAAL framework to both thought experiments helps determine which human factors and strategies improve the chances of surviving and adapting to an electromagnetic event.

A. RESILIENCE AND HUMAN DECISION-MAKING DURING DISASTERS

Several types of federal operating concepts and standards of preparedness to protect critical infrastructure and society against electromagnetic events have been discussed above, but none have identified human behavior as a necessary attribute for mission success. In fact, there is no federal concept or policy that even recognizes that human interaction with systems is part of any critical infrastructure protection concept.[193] This is not only counter-intuitive, as human operators are essential for any system (much less critical infrastructure), but a critical gap the neglects the interaction between human decision making and technological systems during high-consequence events.

The SAAL framework is one way to analyze and create resilient systems that focus on the human-technological relationship.[194] SAAL centers on four key processes that inform whether systems are prepared to adapt to unforeseen and unknown future events: (1) how does a system sense future challenges, (2) how does a system anticipate what to do to when faced with challenges, (3) how does a system adapt and what options are even available to do so,

[192] Thomas et al., "A Resilience Engineering Approach to Integrating Human and Socio-Technical System Capacities and Processes for National Infrastructure Resilience," 1.

[193] Thomas et al., 2.

[194] Thomas et al., 6.

and (4) how are sensing, anticipating, and adapting capacities refined and updated to meet new needs? Each of these processes are sociotechnical, such that they involve humans and technology together. For example, sensing a GMD requires physical sensors and equipment that can detect the event occurrence and human recognition of the collected data. Using the foundations of SAAL (sensing, anticipating, adapting, and learning), private and government organizations can better understand how the human-technological relationship is interdependent and interrelated, which can result in better cognitive decision making and performance of critical infrastructure systems should an EMP/GMD event occur.[195]

A key way to discern the effectiveness of current SAAL processes is by identifying and assessing the ways a system becomes surprised, or experiences events that fall outside normal operations and can lead to catastrophic and cascading failures. There are two classes of surprises described in the resilience literature situational and fundamental.[196] Situational surprises are compatible with past experiences, are well understood, and can be solved with known solutions.[197] An example of a situational surprise would be a EHV power transformer that has no protective equipment overloading and failing during an electromagnetic event from GICs. Conversely, fundamental surprises are those that refute basic beliefs, are hard to model or hypothesize, and introduces factors that are outside of the parameters of most systems.[198] An example of fundamental surprise during an electromagnetic event would be an EHV with GIC protections failing during a GMD event it was designed to survive. Infrastructure failures are often associated with many situational and fundamental surprises, and their identification has helped reveal decision-making issues and resilience improvements (e.g., such as during the Oroville Dam Spillway Failure Incident.[199] Modern technological systems are built to withstand or react to situational surprise because these systems were

[195] Thomas et al., 3.

[196] Daniel Eisenberg, Thomas Seager, and David L. Alderson, "Rethinking Resilience Analytics," *Risk Analysis* 39, no. 9 (September 2019): 1876, https://doi.org/10.1111/risa.13328.

[197] Eisenberg, Seager, and Alderson, 1876.

[198] Eisenberg, Seager, and Alderson, 1876.

[199] John W. France et al., *Independent Forensic Team Report Oroville Dam Spillway Incident*, Independent Forensic Team Report 2018 (Sacramento: California Department of Water Resources, 2018), 1, https://damsafety.org/sites/default/files/files/Independent%20Forensic%20Team%20Report%20Final%2001-05-18.pdf.

created around known parameters for a specific purpose.[200] Fundamental surprises introduce variables that were not expected or put a system in an environment that is outside the parameters for which it was originally intended for.

EMP and GMD events present both situational and fundamental surprise which makes preparing for these events difficult. If these events are properly understood by policymakers and system operators, frameworks could be created that produce systems and human thought processes that mitigate aspects of fundamental surprise. Existing EMP and GMD models have not been able to predict the exact effects on various electrical systems. The eventual cascading effects are not well understood which may create consequences outside of common beliefs and perceptions, causing fundamental surprise. Understanding how fundamental and situational surprise affects cognitive function and technological systems is an important aspect of the SAAL framework because current methodologies that are unable to adapt to new or unfamiliar concepts will ultimately fail when confronted with a fundamental surprise.[201]

B. METHOD FOR SAAL ANALYSIS OF THOUGHT EXPERIMENTS

This thesis develops a method for assessing resilience with the SAAL framework for the thought experiments developed in Chapter III. Our method involves the following repeatable steps:

1. **Develop a timeline of sociotechnical events that occurred during the thought experiment.** Analysis of major infrastructure failures often focuses on a causal chain of events with the intent to discover the root cause or initiating event that led to eventual loss of life and societal impacts.[202] However, this approach ignores the complexity of human decision-making while disasters occur by overlooking organizational context and pressures experienced during failures. Instead, we develop a timeline of the key decisions taken during thought experiments to recognize which organizations

[200] Eisenberg, Seager, and Alderson, "Rethinking Resilience Analytics," September 2019. 1875

[201] Eisenberg, Seager, and Alderson, 1875.

[202] Nancy Leveson, *Engineering a Safer World: Systems Thinking Applied to Safety*, Engineering Systems (Cambridge, Massachusetts: MIT Press, 2012).

are involved, how disaster coordination will need to happen, and how contexts and pressures may influence their effectiveness. This thesis refers to these decisions as sociotechnical events as each event involves the integration of human and technological systems.

2. **Determine when and how sensing, anticipating, adapting, and learning occur.** SAAL processes define four classes of sociotechnical activities taken to respond to disasters. With a complete timeline of sociotechnical events, one can then classify each event as relating to each process. In general, SAAL processes tend to happen in order when experiencing a disaster (sensing → anticipating → adapting → learning). However, some processes may overlap as some sociotechnical events may involve multiple processes (e.g., both sensing and anticipating).

3. **Define the SAAL role performed by key organizations involved in the electromagnetic event**. Labeling sociotechnical events with SAAL processes will reveal which organizations are involved in sensing, anticipating, adapting, and learning. SAAL processes are often performed by different entities, such that an individual or organization involved in sensing may not be involved in adapting. Thus, one can define a sensing, anticipating, adapting, or learning role for key organizations. In some cases, the same organization may have multiple roles. This thesis defines each role they perform and organize these results into a summary table comparing roles across organizations.

4. **Discussion of when and where surprises may occur that impede resilience.** Having organizations fulfilling and performing SAAL roles suggests a capacity to adapt to future, extreme events. However, if SAAL capacities are inefficient, limited, or otherwise missing, situational and fundamental surprises are likely to overwhelm existing systems and responses. Using our timeline of sociotechnical events and table comparing SAAL roles, this thesis discusses the potential for situational and fundamental surprises. In particular, SAAL capacities for managing

situational and fundamental surprises tend to arise from different sociotechnical capacities. Situational surprises are hypothesized to be effectively managed by advanced technological systems, whereas fundamental surprises are managed by human systems and coordination.

C. SAAL ANALYSIS OF THOUGHT EXPERIMENT I (GMD)

Figure 10 presents the results of Steps 1 and 2 our SAAL analysis for to the GMD scenario, providing greater context into the human-technological relationship during the event.

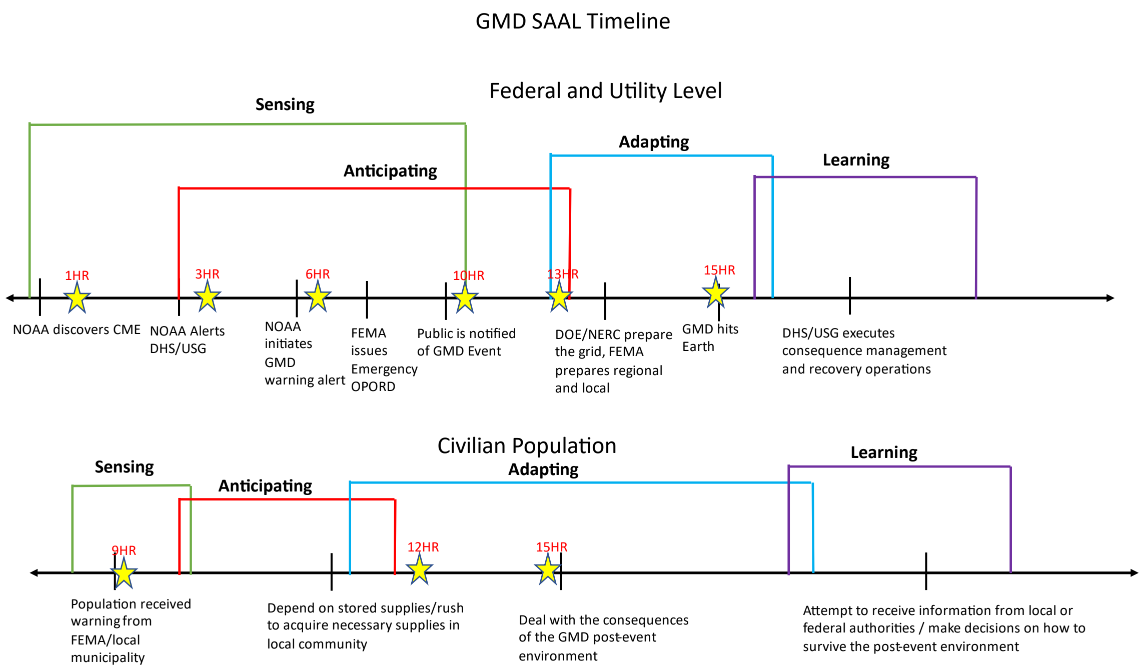

Figure 10. GMD timeline of events with SAAL steps applied

Figure 10 illustrates a timeline of the GMD scenario and divides it into sociotechnical events labelled by SAAL processes. Each timeline is an arrow showing the progression of time where each vertical bar labeled a key sociotechnical event. Because decisions do not follow a linear flow of time, actual timeframes are represented by stars indicating key moments around which decisions are made. SAAL processes are labelled above this timeline to group events and timeframes that involve different roles and responsibilities.

Different elements and organizations can experience the SAAL process at different times, in different orders, and, in some cases, simultaneously. For example, the NOAA initially sensed the GMD event early in the scenario, but the civilian population would sense it via GMD warnings from government agencies at a later time period. Thus, we separate our timeline into two separate, parallel timelines experienced by the federal and utility organizations involved in event recognition and infrastructure response, and the civilian population involved in public response.

The GMD scenario is unique in that present technological systems, such as the NOAA CME monitoring capabilities, had the ability to provide early warning to human operators and enabled government agencies, private utilities, and the public to anticipate and attempt to adapt to the situation as time progressed. Together, this leads to labeling certain organizations like NOAA as performing a sensing role. This thesis organizes these roles in Figure 11 and provide more explanation of each process and role

Agency/Element	Sensing	Anticipating	Adapting	Learning
NOAA	-identified and tracked GMD -issued a Geomagnetic Disturbance warning	-notifies DHS and other relevant agencies	-consequence management and discovery learning	-consequence management and discovery learning
DHS	-disseminated information from NOAA	-distributes GMD warning to internal and external agencies	-consequence management and discovery learning	-consequence management and discovery learning
FEMA	-received GMD warning from the DHS	-issues OPORD to Regional Centers	-prepare for the deployment of key distribution sites (was not successful due to the rapid timeline)	-consequence management and discovery learning
NERC/Electric Utilities	-received GMD warning from DHS	-prepares coordination to configure grid	-coordinate with power utilities to mitigate damage sustained from GMD	-consequence management and discovery learning
Regional and Local Governments	-received OPORD from FEMA	-warns local civilian population	-attempt to disseminate information and aid according to resources available	-consequence management and discovery learning
Civilian population	-received waring from FEMA or local agency	-procures supplies or relied on individual stockpile	-consume supplies or migrated to areas with reliable power	-consequence management and discovery learning

Figure 11. Analysis of each SAAL role performed by an organization or element during the GMD event

1. Sensing

Within the SAAL framework, sensing is the ability to apprehend and interpret information about a stressful event through sensors and human perception in order to make future decisions.[203] During the GMD scenario, several organizations performed sensing roles that provided reaction time and space to allow subordinate organizations to react. Initially, the NOAA, DHS and DOE were able to sense the GMD event via the NOAA's ability to track large events on the surface of the sun, which in turn allowed these agencies to execute their predetermined plan to deal with a GMD event. FEMA was able to disseminate an initial operations order to regional preparedness centers to give some early warning to local governments and the civilian population. The sensing effort at the federal level resulted from NOAA's ability to track solar activity and several agencies' adherence to a standardized federal operating concept for GMD specific events, indicating that a GMD event is a situational surprise at federal agency level. To complement NOAA, NASA also has the ability to track solar events via its Solar Dynamics Observatory, however NASA is listed as part of the Federal Operating Concept for Space Weather Events.

FERC and regional power utility companies were able to sense the GMD warning via communication with DHS and DOE. Sensing allowed FERC and major utility companies the reaction time to configure and protect the grid and flow of power to key areas of the country. Because there are safeguards in place throughout the grid system, the GMD event would be a situational surprise for FERC and power utilities. However, because of the rapid timeline of the GMD event, it was unrealistic to prepare all aspects to provide successful mitigation to the national grid.[204]

The civilian population was able to sense though notifications from FEMA or regional preparedness agencies. Because GMD events are not a common topic or concern for the general civilian population, a GMD warning could be a fundamental surprise due to a lack of understanding of the cascading effects of the GMD scenario.

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

[204] Lina Tran, "NASA Sun Data Helps New Model Predict Big Solar Flares," NASA, July 31, 2021, http://www.nasa.gov/feature/goddard/2020/nasa-sdo-sun-data-helps-new-model-predict-big-solar-flares.

2. Anticipating

Anticipating is "a 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."[205] In the GMD scenario, the primary anticipatory effort from the federal level agencies was the dissemination of information to lower levels of government and to adjacent level agencies such as the DOE and DHS. NOAA's initial warning of a pending GMD event led other agencies to anticipate the effects of the GMD and follow the procedures outlined in the Federal Operating Concept for Space Weather Events.[206]

The initial NOAA warning created a cascading flow of information and further anticipatory efforts from other federal agencies. DHS continued to monitor the situation, disseminate information, and attempted to make all necessary preparations in the short time that was available. FEMA issued an operations order to all regional preparedness centers in an effort to allow subordinate agencies the time to prepare for a long-term electrical outage. The FEMA operations order demonstrates that the steps in the SAAL process can overlap as FEMA provided both sensing and anticipatory actions for the GMD event.

From the FERC and electric utility perspective, anticipation came immediately after DHS and DOE disseminated information on an impending GMD event. FERC and utility companies took anticipatory steps by planning to re-configure the grid based on guidance from the DOE to attempt to mitigate the effects of the GMD event before the full cascading effects were realized.

The civilian population had very little time to anticipate due to the 15-hour timeline that occurred in the GMD scenario. The most prepared households, in terms of having extra supplies, may have different anticipatory actions than those others who were less prepared and would plan on buying groceries or extra water after being informed on an impending GMD via an emergency broadcast message.

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

[206] Department of Homeland Security, *Federal Operating Concept for Impending Space Weather Events*, 1.

3. Adapting

Adapting includes "describes the processes governing system responses to both known and unknown changes in stability and operating performance."[207] In the GMD scenario, the major adapting effort was communicated down from the federal agencies and was executed by the power utility companies and local communities. Once the GMD warnings were disseminated to the regional preparedness centers, the power utility companies attempted to prepare the grid to absorb the impending damage from the GMD event. Each local and regional utility company received guidance prior to the GMD to mitigate the damage as much as possible. Post-event adaptation may consist of efforts to re-energize the grid, known as black start options, in order to make the grid operational in certain areas or provide additional power to areas as required.

The civilian population could have the greatest implications as far as adapting efforts are concerned. Local communities will have to decide how to prepare and adapt in the pre- and post-GMD environments by utilizing generators, using fuel storage techniques, and planning to distribute supplies to local communities in case a long-term power outage occurs. Significant effort may be necessary to ensure that health care facilities can adapt to a long-term power outage that lasts weeks. The state of local communities' preparedness will determine how adaptable the civilian population will be in a post-GMD environment.

4. Learning

Learning "integrates an open loop cycle of interrelatedness among each subgroup of processes (i.e., sensing, anticipating, and adapting) to inform and adjust system outcomes while retaining knowledge for future access."[208] In the GMD scenario, learning would transpire as the GMD event occurred or in the post-event environment. Federal, state, and local agencies would receive feedback on how effective their procedures and policies were on mitigation efforts as the event unfolded. Because the GMD scenario could result in possible communication breakdowns, learning may be a very slow and deliberate process and may not

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

[208] Thomas et al., 7.

occur until the full situation is realized by policymakers. The learning and adapting phases of SAAL could occur in multiple iterations or simultaneously as new variables forced a change in behavior or policy.

The civilian population would only learn and adapt to the GMD event after it occurs as it is not a familiar subject for most people and will most likely be unprepared for such an event. Rural communities may learn and respond differently than urban areas depending on the level of preparedness that was emphasized by federal and local agencies or the preparedness level of individual families before the GMD event occurred. Figure 10 lists how each organization or element reacted during the GMD scenario and demonstrates that after the event occurred, the civilian population and local utilities shared the largest burden of adaptation and learning.

5. Recommendations Based on SAAL analysis for GMD Preparedness

During the GMD scenario, the human technological interaction worked as intended as the NOAA provided the necessary early warning that initiated the federal government's GMD mitigation plan of action. The federal government's technological systems were able to track and identify the GMD and maintain a level of situational surprise as the agencies and systems worked as designed. However, the primary recommendation after analyzing the GMD event though the SAAL framework is that local and regional communities need to put a significant effort into preparedness and rely less on federal agencies such as FEMA for support in the post-event environment. This is not to say that the federal government or agencies like FEMA are incompetent or unhelpful; it is to say that because GMD events occur with little reaction time (9-15 hours), agencies like FEMA will not be able to deploy resources in a timely manner and local communities' preparedness will decide how the civilian population is affected. This calls for proactive measures instead reactive. For example, FEMA's response to Hurricane Ida in August 2021 showcased the agency's quick deployment of emergency assets to the gulf coast region but still took several days to do so.[209] In a GMD

[209] Sara Burnett, "'As Long as It Takes': FEMA, Other Agencies Respond to Ida," AP NEWS, August 8, 2021, https://apnews.com/article/technology-business-health-coronavirus-pandemic-8373de73084250339202efdd7f89bf00.

situation, there would only be hours to respond instead of days. In addition, the ability to communicate to federal agencies may be significantly reduced in a post-GMD environment.

The scenario showcased that state, regional, and local government are the "front line" in the post-GMD event and need to be enabled by federal resources before such an event occurs. The federal government has the resources and systems to forecast and provide early warning of these events, but the consequences, at least initially, are going to have to be delt with at the regional and local level. In 2017 alone there were over 309.5 billion dollars in damage as a result of natural disasters and some statistics show that natural disasters have cost the United States over 1 trillion dollars since 1980.[210] To deal with these costly natural disasters, FEMA and the homeland security enterprise is to continue to fund and enable regional and local communities to mitigate against high impact/low probability events. In addition, local communities need to reinforce a behavioral culture of preparedness at the lowest level possible; the more prepared family units or individuals are against a GMD event, or any natural disaster, the more resources will be available to populations that are more at risk, such as the elderly population, and puts less stress on the overall community.

The current recommendations from most government survival guides are to keep 72 hours to 14 days' worth of supplies per family.[211] These recommendations are far outdated as most people will need to be self-sufficient for longer periods of time, as demonstrated by recent severe natural disasters and massive grid failures that occurred in Texas in 2021, which would pale in comparison to a post-GMD environment.[212] A better recommendation would be three to four weeks of supplies per family household or store such supplies at key locations throughout the community that can be quickly disseminated after an event occurs. The civil defense mindset from the Cold War era is an example of how local communities planned and coordinated for a post-event environment by developing community fallout shelters and

[210] Gavin Smith and Olivia Vila, "A National Evaluation of State and Territory Roles in Hazard Mitigation: Building Local Capacity to Implement FEMA Hazard Mitigation Assistance Grants," *Sustainability (Basel, Switzerland)* 12, no. 23 (2020): 1, https://doi.org/10.3390/su122310013.

[211] The President's National Infrastructure Advisory Council, *Surviving a Catastrophic Power Outage, How to Strenghen the Capabilities of the Nation*, 13.

[212] Halper, "A Texas-Size Failure, Followed by a Familiar Texas Response."

planned for food preparation and other essential services.[213] A similar culture could be utilized for EMP/GMD preparedness in order to reduce the level of surprise when such an event occurs.

Other strategies include emerging technological concepts such as EMP hardened local microgrid concepts that are defined as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island-mode."[214] These micro grid systems could be sufficiently hardened against EMP/GMD events and utilized for a multitude of situations and natural disasters outside of electromagnetic events. Such projects should be funded by FEMA or other federal grants in order to put less stress on the federal and local response in a post-emergency environment. Micro grids could be quicky activated to key areas or smaller communities to ensure emergency services and basic amenities are maintained. Other technological innovations could be transformer programming software that is aware of the increases of atmospheric voltage that occurs during GMD events and could program itself to shield against GIC or maintain a certain level of operation while the event occurs.[215] Strategies such as micro grids and transformer learning software allow more flexibility for human operators and policymakers to adapt and learn from stressful events while maintaining a level of resilience that ensures civilian populations have access to essential services and amenities.

The infrastructure management relationship between public and private organizations is already in place and does not need to be changed. However, the federal government must maintain an appropriate amount of funding, oversight, education and incentives be put in place in order for the private operators of critical infrastructure to maintain or improve their ability

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[213] U.S. Government, *Town of the Times, 1963 Civil Defense Nuclear War and Fallout Shelter Survival* (Periscpe Film, 1963), https://www.youtube.com/watch?v=Sv0EG3LKBow.

[214] Sakshi Mishra et al., "Microgrid Resilience: A Holistic Approach for Assessing Threats, Identifying Vulnerabilities, and Designing Corresponding Mitigation Strategies," *Applied Energy* 264 (April 15, 2020): 2, https://doi.org/10.1016/j.apenergy.2020.114726.

[215] Mate et al., *Analyzing and Mitigating the Impacts of GMD and EMP Events on the Electrical Grid with PowerModelsGMD.Jl*, 1.

to remain resilient against high impact/low probability events such as a large-scale GMD. Throughout the GMD scenario, the SAAL framework determined that the more ready and resilient lower levels of government are, both regional and local, the less stress would put on the federal response and its resources. The human technological processes that have been put in place are effective for a limited form of providing early warning but the protection standards of our current electrical infrastructure may not be enough to stop the cascading effect of GMD events. Because of these factors, a means to provide for a more prepared and resilient civilian population supported by microgrid and other emerging technology is essential to prepare for GMD events and minimize the effects of a fundamental surprise.

D. SAAL ANALYSIS OF THOUGHT EXPERIMENT II (EMP)

The EMP scenario differs greatly from the GMD scenario in that sensing from both the federal level of government and the civilian population did not lead to meaningful anticipatory or adaptive strategies because there was no early warning, as depicted in Figure 12.

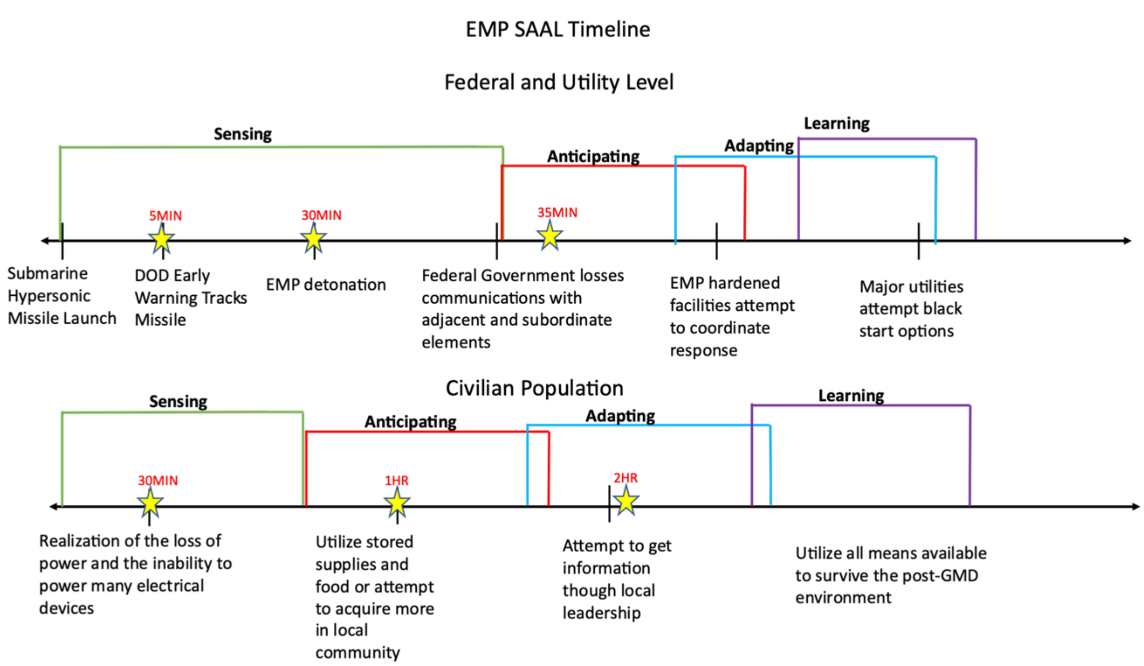

Figure 12. EMP timeline of events with SAAL steps applied

Throughout the EMP scenario, many organizations and individuals were impacted by aspects of fundamental surprise as an EMP event is not only a rare event in our society, but there would be little to no explanation as to why mass power outages were occurring or why certain electronic devices would be inoperable. Compounded with the possibility of mass communication failure, many government agencies and much of the civilian population were struck with fundamental surprise. Using the SAAL principles, the EMP scenario was significantly more detrimental to the national security of the United States than what was seen in the GMD scenario because of the lack of early warning to government agencies and the civilian population. Similar to the GMD scenario, the EMP scenario also reinforced that resilient critical infrastructure systems and a prepared society are paramount in mitigating the effects of an EMP attack.

As demonstrated by the EMP scenario, the lack of early warning and inability to communicate or take adaptive measures created cascading failures which made responses extremely difficult as the civilian population had little to no support. Figure 13 summarized SAAL roles involved in the EMP scenario and contains a detailed explanation of each SAAL role.

Agency/ Element	Sensing	Anticipating	Adapting	Learning
NOAA	-loss of power and unable to communicate to other levels of government	-consequence management and discovery learning	-consequence management and discovery learning	-consequence management and discovery learning
DOD	-tracked incoming hypersonic missile	-attempts to disseminate information on inbound missile threat	-consequence management and discovery learning	-consequence management and discovery learning
DHS	-loss of power and unable to communicate to other levels of government	-consequence management and discovery learning	-consequence management and discovery learning	-consequence management and discovery learning
FEMA	-loss of power and unable to communicate to other levels of government	-consequence management and discovery learning	-consequence management and discovery learning	-consequence management and discovery learning
NERC/Electric Utilities	-loss of power to major geographical areas	-attempts black start options	-consequence management and discovery learning	-consequence management and discovery learning
Regional and Local Governments	-realized power was interrupted or out -unable to communicate to higher levels of government	-attempt to use emergency services to help population -attempt to de-escalate looting or other social deviant behaviors	-attempt to execute local preparedness plans as necessary	-consequence management and discovery learning
Civilian population	-realized power was interrupted or out	-relies on local supplies or attempt to acquire more in the community	-attempt to find information about the situation though physical social networks or local leaders	-consequence management and discovery learning

Figure 13. Analysis of each SAAL role performed by an organization or element during the EMP event

1. Sensing

The primary sensing mechanism at the federal level came from the Department of Defense (DOD), as it is the primary agency that tracks missile threats to American airspace. The current DOD missile defense systems have a low chance of intercepting a hypersonic missile, which are being developed by the United States, Russia, and China.[216] Such weapons are capable of delivering nuclear devices and could achieve an EMP effect via high altitude detonation. Before the warhead was detonated, the DOD air defense networks would be the only means of sensing and would have a very limited window of time to disseminate the information to other levels of government.

Sensing from other levels of government would done though the realization of mass power outages and of various forms of electronics failing to operate. Communication would between agencies or to lower levels of government may be difficult as many forms of modern communication was unreliable. Based on the EMP scenario, early warning to the civilian population was non-existent.

The civilian population accomplished sensing of the EMP scenario by the realization of a lack of power, inoperable electronic devices, and a lack of national emergency communication message. The exclusion of early warning in the EMP scenario forced sensing to be a fundamental surprise to many agencies and overall civilian population.

2. Anticipating

Due to the lack of early warning and fundamental surprise during sensing, the federal government could only communicate through its EMP hardened facilities, which did not enable communication or any anticipatory action to other adjacent or lower levels of government. Anticipation for the civilian population was limited to creating strategies to safeguard and ration supplies as there was no way to determine how long power would be out or why certain electronic devices no longer worked. Because of the lack of messaging and

[216] Stephen Reny, "Nuclear-Armed Hypersonic Weapons and Nuclear Deterrence," *Strategic Studies Quarterly : SSQ* 14, no. 4 (2020): 48.

communication from higher levels of government, the civilian population had very limited means to anticipate and could only depend on the resources found in the local community.

3. Adapting

Adaptation for both government agencies and the civilian population was very difficult due to the lack of feedback from communication networks, as most were inoperable. The civilian population attempted to receive information but faced several obstacles as most services and local municipalities were unable to provide information or were not available. Adaptation in the immediate post-EMP environment was slow as information about the situation was largely unavailable for various government agencies.

Adapting for the civilian population would be especially problematic as there would be no early warning and large geographic areas would be without power. Studies have shown that at least 10% of vehicles on the road would be disabled, especially newer electric vehicles, and traffic control systems would most likely be inoperable.[217] Depending on the time of the detonation, there could be thousands of people stranded on highways and interstates as cars will either be not working or stuck in traffic. In addition, an EMP event will preclude most people from trying to hoard supplies as people will be stranded in whatever situation they are in after the EMP event occurs. The anticipatory effort will hinge on responses from areas that were unaffected from the EMP attack.

4. Learning

Learning was initiated on all levels as a means of trying to understand why large-scale power outages occurred and attempted to find information in order to better survive in the post-EMP environment. Learning at both the federal level and the civilian population would take time to fully understand the ramifications of the EMP attack and come in several iterations. The EMP scenario has a lack of feedback mechanisms as most communication infrastructure would be inoperable.

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[217] Foster Jr. et al., *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack*, 149.

5. Recommendations Based on SAAL Analysis for EMP Preparedness

The lack of early warning to both government agencies and to the civilian population that occurred in the EMP scenario reinforces the previous recommendations that applied to the GMD scenario of a prepared populous and the adoption of new technologies that attempts to limit the chances of fundamental surprise. In the EMP scenario, sensing did not lead to meaningful or productive anticipation, adaptation, or learning which made any attempts at recovery very difficult, as the event was a fundamental surprise for some levels of government and the civilian population. To mitigate these factors, steps need to be taken in order to ensure hardened communication networks are established across all levels of government, some of which should be accessible to the civilian community leadership, and some form of large-scale micro grid backup systems that can be adaptable to fit a variety of situations and contingencies. In addition, since the DOD was the primary sensing effort, steps need to be taken in order to bridge the gap between the DOD and federal civilian agencies such as DOD and NOAA to improve overall situational awareness.

As with the GMD scenario, a culture of preparedness that enables the civilian population to be less reliant on government assistance will be extremely valuable in a post-EMP environment. Communities need to develop standard operating procedures that are put in place before any event occurs to deal with food production shortages, performing medical treatment in austere conditions, water filtration, and some form continuity of government. These type of preparations and mindsets will serve American communities in many forms of natural disasters, not just EMP/GMD events. It cannot be overstated how important preparedness is at the local and community level when dealing in the aftermath of an EMP/ GMD event. Recent events such as the winter Texas power outage in 2021 demonstrate that some communities are unprepared to deal with unexpected disasters. If the same event occurred without the aid of government response and degraded communication capabilities, the outcome could have been much worse. American society should learn from these past events and start making better preparations at the community level, as they will be unable to depend on federal support in the short-term after an EMP event occurs. Strategies may differ between rural and urban communities but both state and federal levels of government need to incentivize these efforts as it will put less stress on government resources.

E. CONCLUSION

This chapter utilized the SAAL framework in order to better understand how human behavior and technology interacted when faced with EMP/GMD events. The recommendations made in this chapter are by no means groundbreaking or complicated; they call for a greater level of preparedness at local levels, create lines of communication between the DOD and domestic agencies for pre-event EMP awareness, and to introduce adaptable technology that can provide an 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 tenants 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.

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 advanced most modern counties 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 thesis does not argue that we must abandon humanity's quest for more technology, it argues that we must have systems in place in order to adapt 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.

An GMD/EMP event, while rare, does have the potential cause significant damage to our critical infrastructure systems and send cascading effects that could impact every single American citizen. Having strategies to deal with post-GMD/EMP environments will not only save lives, it will ensure that America remains secure if such an event ever occurs. Strategies must be implemented to ensure electromagnetic events remain a situational surprise, not a fundamental one. To ensure our systems and society can better prepare for electromagnetic events, the next chapter takes a closer examination at two of the recommendations based on the SAAL framework, black sky options and microgrid technologies, and demonstrates how these recommendations increase resilience based on the Woods framework.

V. RESILIENCE CONCEPTS AND RECOMMENDATIONS TO POTENTIALLY MITIGATE THE EFFECTS OF EMP/GMD EVENTS

Resilience concepts are extremely important for mitigating the effects of EMP/ GMD events. This chapter utilizes David Woods's four concepts of resilience and applies them to two recommendations: 1) the implementation of a national-level hardened microgrid system and 2) the ability to restart the grid in a post-EMP/GMD environment that are referred to as black start options. These recommendations would provide additional resilience to various critical infrastructure systems and allow modern society to be able to both withstand EMP/GMD events and provide the means to recover the electrical grid if it was disabled after such an event occurred. This chapter will do three things: examine the how the Woods resilience concepts apply to EMP/GMD event mitigation, understand the current state of critical infrastructure resilience in the United States, and examine how black start options, which utilize robustness and sustained adaptability, and how hardened microgrids, which utilize the concepts of rebound and graceful extensibility, can provide added resilience and mitigate the effects of EMP/GMD events on critical infrastructure systems

A. WOODS'S RESILIENCE CONCEPTS AND RECOMMENDATIONS

As discussed in Chapter I, Woods describes resilience in four distinct ways: 1) a system's ability to *rebound* from a stressful event and return to normal function, 2) the ability to for a system to operate nominally during stressful events which is known as *robustness,* 3) that ability to utilize *extensibility* and change a system's functions in order to operate in unfamiliar or stressful situations, and 4) a system's ability to utilize networks to *sustainably adapt* to unforeseen events.[218] Whereas the SAAL framework reveals resilience processes, roles, and responsibilities of organizations and the possibility of surprise among them, Woods's four concepts focus on a different aspect of resilience:

[218] Woods, "Four Concepts for Resilience and the Implications for the Future of Resilience Engineering," 1.

what we want systems to achieve in response to events. Having effective SAAL processes suggests adaptive capacities but does not inform what outcomes systems should try to adapt to, just that they can. Effective use of adaptive capacity to be robust, to extend, to rebound, and to sustainably adapt systems is necessary for resilience.

Recommendations based on Woods's resilience concepts include both built infrastructure and human actions to support effective EMP/GMD response. For example, resilience can be achieved by utilizing hardened grid systems that can withstand the effects of EMP/GMD events (robustness), implementing grid architectures that enable new and extended operations such as microgrids that can disconnect and shut down faster than existing systems (extensibility), deploying more and more effective black start equipment to restart key parts of the national grid system disabled by an EMP/GMD event (rebound), or by implementing reconfigurable systems that can more easily change operational and physical capacities for managing EMP/GMD events (adaptability). Likewise, human and decision-making actions can be taken to improve each of these resilience goals, including funding for organizations and research programs that can study and develop technologies to harden grid infrastructure to E1, E2, and high E3 effects (robustness), holding EMP/GMD training and exercises to identify decision bottlenecks and authorities and speed up response activities before and after an event (extensibility), hiring staff and pre-purchasing equipment necessary to repair and recover failed systems after an event (rebound), or by implementing new standards and rules for EMP/GMD resilience across critical infrastructure sectors that force industries to reconfigure and redesign their existing systems (adaptability).

In addition, each resilience concept relates to anticipatory decision taken with post- and pre-event actions in mind. Specifically, rebound and sustained adaptability relate to the actions taken after an EMP/GMD and robustness and extensibility relate to the actions taken before an EMP/GMD. For example, improving the rebound of a power grid (e.g., investing in more line crews, cables, and training to fix failed system) is an anticipatory action taken before an EMP/GMD event occurs. However, fast recovery is only experienced after the impacts of the event are experienced. In contrast, improving robustness of a power grid to can attenuate total damages caused by EMP/GMD, but may do little to speed up recovery operations. Similarly, systems are adapted to future EMP/GMD, but must evolve over time and can only be certain these adaptations are successful after experiencing EMP/GMD. In contrast, technologies and plans to extend system operation can be pre-built into a power grid, and if successful, will attenuate EMP/GMD damages.

Given the breadth of recommendations we could make using these concepts, this chapter will focus on two recommendations related to post- and pre-event actions that would reduce impacts expected from the thought experiments presented in Chapter III. The post-event recommendation is to use black start options which provide a means to restart the national grid if disabled by an EMP/GMD event. Black start options are a source of rebound and extensibility to the electrical grid system after an EMP/GMD related outages by using multiple sources of power production methods to include coal, fossil fuel, nuclear reactors, solar, wind, or hydroelectric in order to restart the grid and provide a means of power to government agencies and the civilian population.

The pre-event recommendation is to create a national system of EMP/GMD-hardened microgrids that are able to disconnect from the national grid if an EMP/GMD event occurred, providing power to critical nodes and infrastructure. This would ensure all levels of government have a means to provide services to the civilian population and recover from an EMP/GMD event. Microgrid systems are robust and extensible because they have the ability to disconnect from the national grid system during an EMP/GMD event to continue providing power as the system would be designed to sustain critical infrastructure systems during an EMP/GMD event. However, updating the existing power system to include hardened microgrids may require improved adaptability as well to reconfigure existing networks and implement more advance controls and management systems.

Each of these recommendations require significant investment and research, but would also provide a higher level of resilience than America experiences today. If implemented, black start recommendations would provide faster more effective rebound, where hardened microgrids would provide greater robustness and operational extensibility. In addition, these recommendations provide a means to counteract and quickly recover from EMP/GMD events, regardless of whether federal agencies have early warning of such an event.

B. CURRENT STATE OF RESILIENCE IN THE UNITED STATES

In order to provide realistic recommendations that can mitigate the effects of EMP/GMD events this section will first illustrate that the current state of resilience in American infrastructure is lacking. Resilience is not an unfamiliar concept to federal agencies or civilian operated utility-companies as several natural and man-made disasters have occurred from 2001 to the present day. Various government agencies first required an all-hazard approach to resilience in the wake of 9/11, Hurricane Katrina and Super Strom Sandy.[219] Based on the federal government's all-hazards approach and Presidential Policy Directive (PPD) 21, critical infrastructure systems needed to incorporate resilience concepts to either withstand stressful events or quicky return to normal operations after a stressful event occurred. As of 2021, DHS, DOE, and the DOD are all studying resilience frameworks and applying them to achieve resilience at regional and national levels.[220]

Despite these efforts, America's critical infrastructure systems are in poor condition and are not as resilient as they need to be to withstand stressful events. In 2021, the American Society of Civil Engineers (ASCE) assessed that America's critical infrastructure systems are well below average and need essential upgrades to ensure sustained operations.[221] There are several reasons why America's critical infrastructure is not at a high level of resilience but chief among them is that resilience, and the management of critical infrastructure systems, is interdisciplinary and requires the input, expertise, and cooperation of public and private entities, which can be difficult to orchestrate.[222] As the Texas winter power grid outages have demonstrated, many of our critical infrastructure

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219 Alderson, "Overcoming Barriers to Greater Scientific Understanding of Critical Infrastructure Resilience," 67.

220 Alderson, 67.

221 "ASCE's 2021 American Infrastructure Report Card | GPA: C-," *ASCE's 2021 Infrastructure Report Card* | (blog), January 11, 2017, https://infrastructurereportcard.org/.

222 Alderson, "Overcoming Barriers to Greater Scientific Understanding of Critical Infrastructure Resilience," 69.

systems are unable to cope with new or unexpected events.[223] Critical infrastructure systems of the future need to incorporate resilience concepts that ensure the ability to withstand events as they are occurring or have the ability to quickly regain function after a stressful event occurs.

EMP/GMD events require systems that can adapt or withstand against forces that are rarely experienced on Earth. These events will induce massive amounts of atmospheric voltage and GIC that is introduced into the atmosphere that, as previously discussed, creates enormous stress on critical infrastructure systems. The implementation of these recommendations will create resilient systems that could respond effectively to various forms of stressful events, not just EMP/GMD.

C. POST-EVENT OPTION: BLACK START RECOVERY OPTIONS (REBOUND AND GRACEFUL EXTENSIBILITY)

Current black start 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.[224] Black start options are designed to respond to black sky events, which 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."[225] 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."[226] 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.[227] Currently, most power production facilities, to include nuclear reactors are not constructed to withstand the effects

[223] Halper, "A Texas-Size Failure, Followed by a Familiar Texas Response."

[224] Greene, "Nuclear Power," 9.

[225] Greene, 5.

[226] Greene, 9.

[227] Mishra et al., "Microgrid Resilience," 2.

of EMP/GMD events.[228] In order to utilize black start options for EMP/GMD events, these black start 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 concreate or steel protection that includes specialized doors, grounding procedures, and enough backup power for up to 30 days of operation.[229] While the cost of hardening these faculties would have huge economic and financial requirements, such measures would ensure 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.[230] 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.[231] As 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.

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[228] 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/.

[229] 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, Virgina: 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.

[230] 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.

[231] Garcia et al., iv.

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.[232] There are a variety of dangers that occur when nuclear power plants are forced to come off the national grid, including nuclear meltdowns, after EMP/GMD event. 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.[233] 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.[234] 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.[235] 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 concreate structures underground, protecting them some protection against electromagnetic events, but would still need to be sufficiently hardened.[236] The FLEX program was not created specifically for EMP/GMD events but could extend power to the grid as a long-term option.

Black start frameworks can provide policy makers and private sector leaders a strategy that would serve the United States in 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

[232] Greene, "Nuclear Power," 16.

[233] Greene, 15.

[234] Greene, 14.

[235] Greene, 13.

[236] Greene, 14.

areas but could then be used to transport power to other effected areas as most grid interconnections would still be intact. Utilizing Woods's concepts of robustness and graceful extensibility, EMP/GMD hardened black start options would be a key strategy for recovering from EMP/GMD events.

D. PRE-EVENT OPTION: HARDENED MICROGRID INFRASTRUCTURE (ROBUSTNESS AND SUSTAINED ADAPTABILITY)

The second recommendation includes the utilization of interconnected hardened microgrid systems. Hardened microgrids have the ability to operate off of the national grid but can also function in stand-alone island mode in order to ensure key infrastructure is able to function during an EMP/GMD event utilizing the concepts of robustness and sustained adaptability. Various microgrid systems, hardened the MIL-STD-188-125-1 standard, provides 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.[237] Modern microgrids are being constructed for three main purposes throughout the world; energy security, economic benefits, and clean energy.[238] However, the main reason for microgrid investment in the United States is added resilience and reliability of the electrical grid.[239] The United States now contributes 42% of the world microgrid market, all of which provide both renewable and diesel sources of power generation .[240] As climate change and natural disasters continue to cost taxpayers billions of dollars a year, microgrid concepts provide a unique solution to continue to provide power to affected areas that are less vulnerable to cascading effects that occur when large

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

238 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.

239 Hirsch, Parag, and Guerrero, 404.

240 Hirsch, Parag, and Guerrero, 404.

portions of the grid are affected. 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, creates systems that can withstand 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.[241]

Microgrid systems are not without challenges or controversy as these systems have various 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.[242] 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.[243] 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.

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

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

243 Hirsch, Parag, and Guerrero, 409.

Hardened microgrid systems are a huge investment but offer improved energy security and resilience that would provide critical capabilities in the aftermath of an EMP/GMD event. As renewable energy sources, such as solar and wind turbine techniques become priced comparably to traditional sources of power, adoption of renewable microgrid technology will become the norm rather than exception.[244] However, all of these systems are at risk of the effects of EMP/GMD events as they rely on wireless and SCADA technology. Hardening these systems would prove to be one of the most challenging aspects of microgrid implementation but starting with key strategic locations could eventually proliferate hardening techniques to commercial or residential areas. Hardened large-scale microgrid systems would provide a level of resilience, though robustness and sustained adaptability, that could significantly reduce the effects of an EMP/GMD event and allow various critical infrastructure systems the ability to operate in a variety of stressful conditions. Microgrids would also provide the civilian population access to critical services even when portions of the national grid were disabled, providing stability and rule of law that would be otherwise unavailable.

E. CONCLUSION

Black start options and hardened microgrids are two recommendations that could be implemented to improve the overall resilience of the electrical grid, and other critical infrastructure systems, against an EMP/GMD event. Implementing these systems would not be easy or inexpensive but, learning from historical examples of GMDs alone, would prove to be a worthy investment as it is only a matter of time before an electromagnetic event will occur on Earth. Using a combination of elements from Woods's resilience frameworks, these recommendations provide a flexible and adaptable approach to combat the effects of electromagnetic events and numerous other contingencies. The added value of improving the overall resilience of America's critical infrastructure systems has lasting effects for economic prosperity and national security. As natural disasters and climate change continue to validate that the current level of resilience of American infrastructure is inadequate, an EMP/GMD event could have catastrophic consequences not only on the

244 Hirsch, Parag, and Guerrero, 409.

civilian population and government, but America's position as a global hegemon. In order for America to maintain its position in the global order, implementing added resilience to critical infrastructure systems should be non-negotiable.

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VI. CONCLUSION AND AREAS OF FUTURE RESEARCH

The objective of this thesis was to assess the current vulnerabilities that exist within America's infrastructure against EMP/GMD events and produce recommendations that could mitigate against this threat. By analyzing the current trends in electrical infrastructure and government regulations to protect against electromagnetic events, it is apparent that we are setting a low bar in terms of protection. As previously mentioned, NERC regulations are preparing for the lowest common denominator, the 1989 GMD event, and not more powerful events that have been documented as being much more destructive.[245] Based on this assessment, it would appear that the United States is not as prepared as it could be for large a large-scale GMD or an adversarial EMP attack.

A. SUMMARY OF KEY RESULTS

The results and analysis of both thought experiments recommended higher levels of preparedness at regional and local levels and the implementation of new and existing technology that would 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 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 that entail fundamental surprise. EMP/GMD events could make entire regions lose the ability to produce power, provide medical assistance, and impede food/water production which would incur enormous stress on the all levels of government.

Despite well-studied and known vulnerabilities of some systems to EMP/GMD events, this thesis was able to identify certain decision-making factors that influence national resilience through thought experiments. By analyzing how EMP and GMD events

[245] Wang et al., "Power Grid Resilience to Electromagnetic Pulse (EMP) Disturbances," 2.

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's frameworks, this thesis found that by using a combination of policy implementations, such as focusing preparedness at local levels and better communication between the DOD and DHS, combined with technological assets, such as hardened microgrids and black start options, there are ways to mitigate the threat of EMP/GMD events. Figures 14 and 15 display an overview of the analysis based on the thought experiments and the SAAL/Woods's frameworks. Based on these findings, the public and private sector need to continue to work together to provide added protection against electromagnetic events though the implementation of new polices and integration of emerging technologies.

	Key Attributes of Event	SAAL Framework
Thought Experiment 1 (GMD)	- widespread effects (continental) - GIC (E3) only effected electrical transformers - 9-15 hours of early warning via NOAA - Primary response form domestic agencies (DHS, DOE, state, and local)	**Sensing:** NOAA **Anticipating:** 9-15 hour warning via NOAA, hoarding by civilian population, mitigation from DHS **Adapting:** Federal Operating Concept (DHS, NOAA, DOE, FEMA) drove responses by federal and local agencies **Learning:** post event (local-level preparedness is key)
Thought Experiment 2 (EMP)	- Regional effects (multi-state) - E1, E2, E3 waveforms affected all electronic equipment - 30 min early warning via DOD - no meaningful response from domestic agencies due to little to no early warning	**Sensing:** DOD **Anticipating:** 30 min warning, no real way to effectively prepare **Adapting:** no meaningful adaptation besides deploying assets from unaffected regions **Learning:** post event (DOD and DHS integration is key for response and post-event coordination)

Figure 14. Overview of the key attributes from thought experiments and findings based on the SAAL framework

Woods's Resilience Frameworks (applies to both Thought Experiments)

Black Start Options (Post-Event): Rebound and Graceful Extensibility
- hydroelectric dams
- nuclear reactors

Hardened Microgrids (Pre-Event): Robustness and Sustained Adaptability
- assets hardened as per MIL-STD-188-125-1
- renewable and diesel power sources
- initially implemented to strategic government areas or population centers to mitigate against the cascading effects of disruption of the national grid
- government standard needs to be implemented to ensure national interoperability

Figure 15. Overview of key findings from the Woods framework

Overall, there are methodological and practical results and outcomes of this thesis. The methodological resilience can be summarized as the following:

- **Thought experiments provide a useful context to identify SAAL roles and responsibilities before a catastrophic event.** Despite a significant amount of work identifying and measuring the impacts, effects, and potential responses to GMDs and EMPs, no research integrated these elements into actual decisions and their timelines. This information is helpful for organizations that have never considered GMD and EMP threats to understand how long they have to respond and where in the event process they may be involved. In particular, state and local emergency management benefit from this analysis to recognize how the federal government and utilities might coordinate, to support their integrated response in this system.

- **SAAL analysis provides a useful framework to identify when and how surprises might affect even well-prepared systems.** Situational and fundamental surprises require different systems to manage them, but without knowledge of SAAL roles and processes, there is limited capacity to identify when or which organization might be surprised.

- **Woods's resilience concepts help organize and identify solutions to achieve resilience outcomes, even for low-probability, high-impact events.** Federal resilience policies focus attention only on robustness and rebound capacities, but extensibility and adaptability are additional needs for national resilience. By considering all four outcomes for systems, policymakers can identify existing needs and nascent technologies to improve resilience.

The practical results for electromagnetic event resilience are summarized as:

- **SAAL:** NOAA and DOD organizations will perform sensing roles to GMDs and EMPs, respectively, suggesting a national need for similar information sharing and coordination relationships between NOAA, the DOD, and related agencies.

- **SAAL:** There is no federal operating concept for large-scale EMP events as GMD operating concepts will not work fast enough to respond to the speed of an EMP. An entirely different operating concept needs to be developed.

- **SAAL:** Learning from GMDs and EMPs emphasize different levels of government. GMDs emphasize local learning and after-action coordination, whereas EMPs emphasize federal learning and after-action coordination.

- **SAAL:** Individual and community level preparedness is essential for providing the civilian population with necessary supplies that are critical when long term power outages occur. This should include, but not limited to, water purification/distribution, long-term food supplies, and standard operating procedures that localities practice in order to mitigate any civil unrest that may occur.

- **Woods's Concepts:** Blackstart plans and practices need to consider GMD and EMP threats. A GMD event will provide some early warning so that power utilities can execute any necessary actions to prepare blackstart options before the event occurs. EMP, on the other hand, calls for blackstart options that are able to be implemented rapidly, which would require significant EMP/GMD hardening of designated blackstart assets and dedicated personnel that are trained for such a contingency.

- **Woods'sConcepts:** EMP hardened microgrids can provide robustness to EMP/GMD and novel system architectures for resilience. The ability for communities to disconnect from the national grid, prior to or during an electromagnetic event, enables key critical infrastructure sectors to continue to operate and provide services to the civilian population and government agencies. These systems would also shorten the recovery period in a post-EMP/GMD environment.

B. LIMITATIONS AND FUTURE WORK

There are several shortcomings that limit the efficacy of the analysis and recommendations presented in this thesis. Foremost, because this thesis did not include classified information or have the ability to conduct tests in simulated EMP/GMD environments, further research should be conducted in order to provide greater insight on the effects of EMP/GMD events. Due to the fact that 5G technology is rapidly advancing in almost all developed counties, research should be conducted to determine how susceptible 5G networks are to EMP/GMD events and if there are certain protections that can be implemented to protect these networks.

In addition, future research on emerging technology that can be used to protect EHV transformers would be beneficial as self-diagnostic and self-healing network software against increased atmospheric GIC is still being developed but could have enormous value in the future. There seems to be significant gaps in information related to how we can protect EHV transformers before a GMD occurs. While this information may be classified, it would be advantageous for the power utility industry to have a firm understanding of how to best configure the national grid to mitigate the effects of GMD events. Research from Cornell University has shown that software applications relating to the protection of EHV transformers against electromagnetic events is possible and has the potential to create robust power grids that can continue to operate during EMP/GMD events.[246] Furthering this type of research will have significant benefits to the public and private sector.

As previously stated throughout this thesis, EMP/GMD events are rare events that have potentially disastrous consequences for all nations on Earth. While most of the material in this thesis focused on the impacts to society and critical infrastructure of the United States, all world governments should take EMP/GMD events seriously and ask themselves if they are truly prepared for such a significant incident. How would population of the modern age react to prolonged periods of no power, running water, or access to medical care? These are the possible outcomes that could occur in a post-EMP/GMD environment. The COVID-19 pandemic demonstrated how fragile our interconnected world as it destabilized the global economy, supply chains, and society at large. A large-scale electromagnetic event such as a EMP or GMD would prove to be a much worse reality that could trigger large-scale civil unrest that has rarely been experienced in modern times. Despite these threats, this thesis demonstrated that current and emerging technology has the ability to mitigate the effects of electromagnetic events through resilience frameworks and human-technological systems that can anticipate and adapt to changing conditions. It is ultimately up to policymakers to choose if the threat of an EMP/GMD event is worth the investment to protect our way of life.

[246] Mate et al., *Analyzing and Mitigating the Impacts of GMD and EMP Events on the Electrical Grid with PowerModelsGMD.Jl*, 1.

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