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A Survey of Preventive and Remediating Mitigations for High-Altitude Electromagnetic Pulse Impacts on the United States Electric Power Grid

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Unlimited Release 35 words or less abstract: This survey of relatively recent literature showcases the complicated nature of HEMP resilience planning involving threat characterization and vulnerability assessment, application of current and upcoming technologies, logistical and planning considerations, and provides future research recommendations.

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The United States electric power grid is "the largest single capital-intensive infrastructure in North America" [1] and is essential to the operation of all other critical infrastructures and, thus, modern society [2]. High-Altitude Electromagnetic Pulse (HEMP) is unique among the types of anthropogenic threats faced by the grid in its potential to simultaneously disrupt many devices across a very wide geographical area for an uncertain amount of time [3] [4] [1] [5]. The grid, comprised of the generation, transmission, and distribution systems and their loads, has some known vulnerabilities to early-time HEMP (E1) and late-time HEMP (E3), and many areas where the vulnerability is not fully known [4] [6] [7] [8]. Intermediate-time HEMP (E2) is not considered a significant concern thanks to lightning arrestors in-place today [9] [4]. Recent work conducted at Sandia National Laboratories demonstrated certain grid components may be more resilient than previously thought [10]. The power grid relies on a complex web of interdependent connections with other critical infrastructure networks [11], many of which are also susceptible to HEMP attack and can rely on aging infrastructures [6] [12] [13] [14] [15]. The interconnections between infrastructure networks may not be obviously vulnerable, and the loss of any dependent network could render the grid inoperable [1] [16] [11].

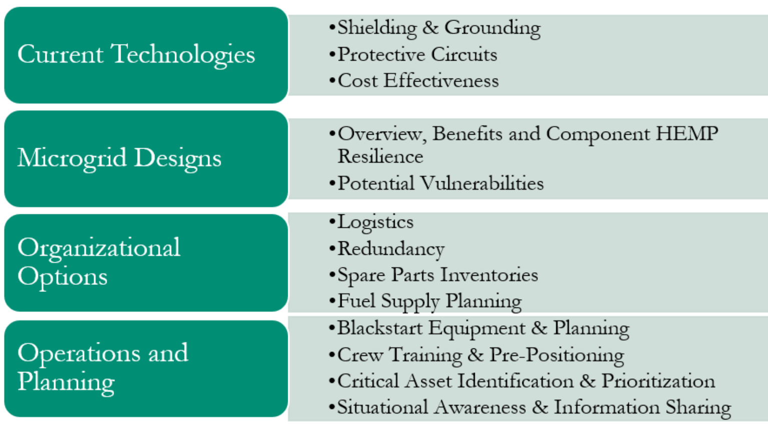

Figure 1: Sections used in the report to organize the HEMP mitigation options.

Mitigation options were defined across the following main categories (

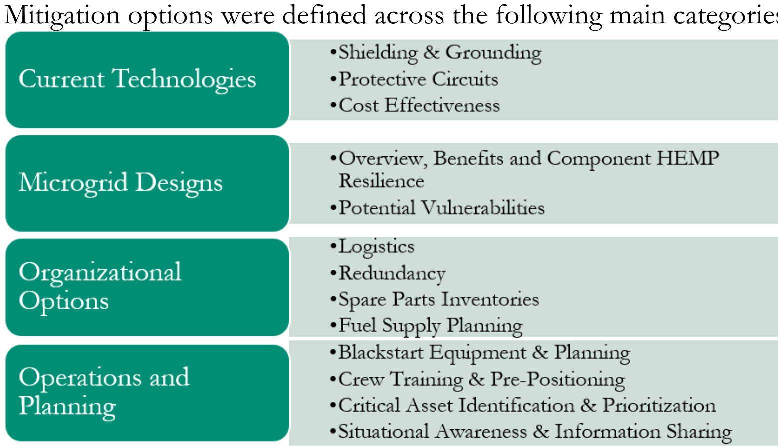

Figure 1): (i) current technologies; (ii) microgrid designs; (iii) organizational options; and (iv) operations and planning. Current technologies, including shielding and protective devices, are known to mitigate damage from HEMP, and E1 in particular [17]. Shielding, in the form of Faraday cages and similar protections, can be applied to facilities or rooms therein, equipment, and lines and cables to reduce or eliminate induced voltages and currents [4] [3] [18]. Proper grounding, elimination of gaps in shielding, and properly installed ingress points for cables are all recommended to prevent harmful transients from entering a facility and causing damage to sensitive equipment [5] [18] [10]. Protective devices, such as filters and surge protection devices, can divert and block damaging power flows from reaching sensitive equipment [19]. However, the rise time for E1 is too fast for Transient Voltage Surge Suppressors [20] and Digital Protective Relays [4] to protect

equipment. Options to eliminate GICs, such as neutral blocking devices, neutral resistors and series capacitors, are effective to protect transformers from E3 [14] [7] [21] [22]. HEMP mitigation can be costly to implement and is recommended for critical equipment and buildings at construction time wherever possible [5] [15] [23] [17].

Microgrids deployed at scale may reduce a cascading outage (primarily from E3 HEMP), could enable faster restoration of service to load, and have been recommended for military bases [11] [4] [1] [14]. They benefit from technology that enables automated isolation from the primary grid during an outage (if connected), and to resynchronize and reconnect themselves afterward [13]. Recent testing has shown certain microgrid components are resilient to HEMP, including many types of photovoltaic systems [24] [25] and residential microinverters [26]. However, distributed intelligence, upcoming communication/control systems, and autonomous systems leveraged by microgrids are not tested against HEMP [4] and could introduce new vulnerabilities [13], particularly from cyber threats [11]. While EMP-protected microgrid development is underway with DTRA and at least 40 other companies [3], more research is needed to quantify the impacts of HEMP on microgrid designs and their individual components [32] [7] [6] [13].

Organizational options include logistics, redundancy, spare parts inventories, and fuel supply planning options. Logistical mitigation options are critical to consider in advance of an event, including redundancy of system components and power flow paths, spare parts inventories, and fuel supply planning considerations [4] [13]. Separately, redundancy in terms of power flow paths would offer a reduction in the number of critical power flows and components to remove single points of failure and therefore increase resilience against a broader range of threats [11] [2]. Spare parts, fuel, and recovery crews should be made available, as current spare parts inventories could be insufficient for a major event [13] [2] [9] [17]. Evaluation of transformer spares is advised even for Large Power Transformers, despite the low risk of damage from E3 [4] [10] [22], given their limited spare quantities [2]. Sparing strategies should account for transformer damage at all three phases [2] [4]. Fuel supply should be pre-planned for restoration operations including extended periods of backup generator use, generators with multi-fuel capability should be explored, and critical fuel supply systems should be protected from HEMP [1] [27] [28]. To reduce recovery time, shielded equipment should be pre-positioned across the country, including backup generators, fuel, and communications [1] [27]. Certain generation plants, such as natural gas generators, are dependent on fuel pipeline systems and typically have no backup power systems [18] [11]. Natural gas accounted for 33% of the U.S. electric power sector's primary energy consumption and 40% of total utility-scale U.S. electricity generation by all sectors in 2020 [29]. Generation plants reliant on these systems would cease to function once their pipeline systems are rendered inoperable and after any backups are exhausted [5] [1]. Concerning nuclear reactors, while the primary impact is expected to be the loss of external power from the grid, the resilience of nuclear power plant backup systems to HEMP is a risk to ensuring safe shutdown is always possible [28].

Operations and planning considerations such as emergency planning, preparedness, and training are critical goals that involve industry, government agencies, and national laboratories. An increased number of blackstart units should be installed, hardened against HEMP, and ensured they can use multiple fuels [1] [9]. Recovery crews should understand how recovery from HEMP might be different than recovery from more common threats [12] [28] [4] [30] [9] [27]. Recovery efforts should be prioritized for critical equipment and facilities such that higher priority assets are restored before those having lower priority [31]. Impacts to the transmission system from E1 and E3 can degrade situational awareness [22] provided by systems such as SCADA, ICCP, and EMS, and protection of this capability should be prioritized to reduce recovery time [4]. Information sharing must increase between government, academia, and industry on topics such as EMP effects, vulnerabilities, and infrastructure resilience [32] [27] [12] [28] [33] [6].

Many research challenges surround the topic of HEMP, including how it could threaten the power grid and how to allocate mitigation and recovery resources to protect electric utility systems. Vulnerability to HEMP is critically understudied and there is a lack of empirical data and publicly available information that would direct industry investments in mitigation research [27] [5] [4] [12] [34]. Many unknowns exist in terms of threat space, power grid impacts, and mitigation options to protect against this threat [31] [5]. New research is needed to determine how larger, bulk electric systems can be shielded and protected from HEMP given their significant complexity and economic constraints faced by utilities [27] [5] [4] [12]. Many new and upcoming systems rely on electronic components that could be more vulnerable than older systems to HEMP and cyber threats [5]. New research could determine how to harden those systems and to develop new analytic tools and capabilities to provide better automation and decision support to operators and utilities [5] [11] [2]. Separately, new models and analytical tools are needed to assess logistical mitigation options and how resources should be allocated pre- and post-HEMP event [11]. Finally, work is needed to determine how operations and planning can be improved and implemented to minimize the recovery period from a HEMP event [1] [9] [5].

Disclaimer: key references are provided in this summary and more will be provided in the final submission.

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