Protecting America's Electric Grid Against Electromagnetic Pulse Attack

March 2017

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Executive Summary

The asymmetric threat with the most severe consequences to the nation's electric grid is arguably the high-altitude burst electromagnetic pulse (EMP)[1] that occurs when a nuclear warhead is detonated 30-400 kilometers above the Earth's surface. Specifically, a single weapon could black out the entire North American continent for periods ranging from months to years resulting in the breakdown of governance and loss of the majority of our population. EMP debilitates infrastructures essential for life support, national security, and economic enterprise. Chief among these is the electric power grid and its supporting infrastructures including communication/data networks, fuel supply and water. Given the critical importance of reliable electric power, it is essential that the United States protect, mitigate, respond to, and recover from the potentially devastating effects of EMP.

Several nation states today possess nuclear weapons which could be used to attack the United States and our allies with EMP. Other nation states and non-state actors may acquire such weapons in the future despite non-proliferation efforts. The nature of an EMP detonation is such that it can occur with little or no warning, severely constricting the ability of operational-based strategies to limit damage as there is insufficient time to implement such strategies. Therefore, the response to EMP threats necessarily involves measures that harden assets to reduce their vulnerability to damage. Improved response and recovery actions are also important to limit the duration of any outage.

In 2008, the Commission to Assess the Threat to the United States from Electromagnetic Pulse, made a compelling case for protecting critical infrastructure against the nuclear electromagnetic pulse (EMP) and geomagnetic disturbances (GMD) caused by severe solar storms. Their Critical Infrastructure Report explains EMP effects, consequences, and protection means for critical infrastructure sectors. EMP and GMD are particularly challenging in that they interfere with electrical power and electronic data, control, transmission, and communication systems organic to nearly all critical infrastructures. The affected geography may be continental in scale. EMP and GMD events thus represent a class of high-consequence disasters that are unique in their coverage, ubiquity, and simultaneous system debilitation. These wide-area disasters have not yet occurred within the United States yet require particular attention with regard to preparedness and recovery since assistance from non-affected regions of the nation could be scarce or nonexistent. With focused preparedness planning and using available protection engineering tools, such disasters are preventable.

[1] There are many sources of EMP including high altitude nuclear detonations, solar storms, nuclear ground detonations, and RF weapons. In this monograph, we use EMP to refer to that produced by a nuclear weapon detonated at high altitudes (30-400km) above the Earth's surface. Many references use the HEMP acronym to refer to the high-altitude burst EMP.

In the near term, the outlook for grid EMP protection is poor because of resistance by electric utilities and low prioritization by government authorities. Of particular concern, the Federal Energy Regulatory Commission (FERC), North American Electric Reliability Corporation (NERC) and the U.S. electric power industry have chosen not to address the EMP threat, arguing that this is the responsibility of federal security agencies—Department of Defense (DoD), Department of Homeland Security (DHS) and Department of Energy (DOE). FERC and NERC have developed benchmarks for solar GMD but these benchmarks are ineffective against EMP and also fall far short of assuring GMD resilience.

We must come to grips as a nation with the EMP/GMD preparedness challenges. The consequences of these threats are preventable. The good news is that the engineering tools are available to protect a meaningful set of high-priority infrastructures. There are a number of initiatives that would greatly aid in this endeavor:

First, a designated national executive agency and director is needed. DHS and DoD are likely candidates. Of these, DoD has the most experience. The first order of business should be a national EMP/GMD protection plan and a set of national planning scenarios.

Second, let us begin a national program to protect the electric power grid, including essential supporting infrastructures used for fuel supply and communication.

Third, Congress should address problems inherent in the regulation of electric reliability as conceived in the Energy Policy Act of 2005. The present FERC-NERC arrangement has proven ineffective with respect to EMP/GMD preparedness. Establishing a new independent commission solely focused on electric grid reliability would be helpful – a commission with the power to issue and enforce regulations, similar to the Nuclear Regulatory Commission (NRC).

On a positive note, we have the engineering know-how and tools to protect ourselves. EMP protection is well within US engineering capabilities. The protection technology and methods are available. What is lacking is resolve.

The EMP Threat

Since the nuclear weapon atmospheric test days of the 1950s, it has been known that a single nuclear weapon detonated at altitudes from about 30-400 kilometers generates a strong electromagnetic pulse (EMP) that can disrupt electronic systems on the ground at large distances.[2] During the Cold War, EMP was considered in the context of massive nuclear exchanges where physical destruction of infrastructure was the chief concern. At that time,

[2] Dr. William R. Graham, Chairman, Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack, Statement before the House Armed Services Committee, July 10, 2008

EMP effects were considered by many to be ephemeral, second order effects in comparison to direct blast/thermal/radiation effects from surface bursts in the context of mutually-assured-destruction (or MAD) scenarios. However, as information warfare and infrastructure debilitation objectives have gained prominence and success in military operations, the likelihood of high altitude nuclear scenarios has gained wider acceptance among strategic planners. When viewed in the context of infrastructure debilitation, high altitude nuclear attacks begin to make sense as a primary tactic to deny or delay a nation's ability to respond. It is now conceivable that EMP may be used strategically either as a precursor attack or by itself to debilitate U.S. electric power and communication networks.[3]

High altitude nuclear bursts generate two main EMP types that may be referred to as the "fast pulse" and the "slow pulse." The fast pulse EMP field, also referred to as E1, is created by gamma ray interaction with stratospheric air molecules. It peaks at tens of kilovolts per meter in a few nanoseconds, and lasts for a few hundred nanoseconds. The broad-band frequency content of E1 (0-1000 megahertz) enables it to couple to electrical and electronic systems in general, regardless of the length of their penetrating cables and antenna lines. Induced currents range into the 1,000s of amperes. Exposed systems may be upset or permanently damaged.[4]

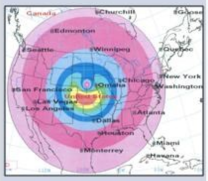
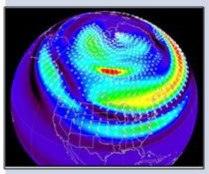
The "slow pulse" EMP, also referred to as E3, is caused by the distortion of the Earth's magnetic field lines due to the expanding nuclear fireball and rising of heated and ionized layers of the ionosphere. The change of the magnetic field at the Earth's surface induces currents of hundreds to thousands of amperes in long conducting lines (with lengths of a few kilometers or greater) that damage components of the electric power grid itself as well as powered systems. Long-line communication systems are also affected, including copper as well as fiber-optic lines with repeaters. Transoceanic cables are a prime example of the latter.[5]

Solar storm-caused geomagnetic disturbances (GMDs) also generate over-voltages in long-line systems affecting electric power and communication transmission networks in a manner similar to EMP/E3. It is important to note that protecting long-line systems against EMP (E1 and E3) also affords protection against GMD effects. The converse is not true. Protecting electric

[3] G. H. Baker, EMP: A National-Scale Threat to the U.S. Infrastructure, The Critical Infrastructure Protection Report, George Mason University, April 2007.
[4] The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid, Oak Ridge National Laboratory, Edward Savage, James Gilbert and William Radasky, Metatech Corporation, January 2010.
[5] The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid, Oak Ridge Nation Laboratory, James Gilbert, John Kappenman, William Radasky and Edward Savage, Metatech Corporation, January 2010.

transmission systems against solar storm GMD/E3 does protect against EMP/E3 – but defending against the fast pulse EMP/E1 requires different equipment.

A summary of the nuclear and solar environments of concern is provided in the table below.

	THREAT	Environments	Susceptible Systems
	High Altitude EMP	Fast Pulse E1	Long-line and short-line electrical and electronic systems
		Slow Pulse E3	Long-line network systems incl. electric power grid, terrestrial and undersea comm. lines, pipelines
	Solar Super Storms	Geomagnetic Disturbance	Long-line network systems incl. electric power grid, terrestrial and undersea comm. lines, pipelines

Protection Priorities

Similar to protecting critical infrastructure against any hazard, it will be important to develop risk-based priority approaches for the solar GMD and nuclear EMP threats, recognizing that it will be fiscally impracticable to protect everything. Because electromagnetic threat environments are measured in volts per meter (V/m), a given system’s vulnerability increases with the length of its connecting lines. Because the electric power grid and long-haul communications network (including telephone and Internet) deliver services on long-lines, these infrastructures are the most vulnerable to EMP and GMD. It is ironic that the infrastructures *most vulnerable* to EMP and GMD are arguably the *most critical* to society, not only for day-to-day enterprise and life support, but also to enable recovery should disasters occur.

Since a simple measure of risk is the multiplicative product of vulnerability and criticality, the electric power and the long-haul telecommunications networks sit at the top of the risk ranking hierarchy.[6] Thus, attention to the electric power grid and long-haul communications infrastructures would bring major benefits to national resiliency. Of these two, the electric power grid is the arguably the most important to protect since all other infrastructures ride on

[6] G.H. Baker, Risk-Based Critical Infrastructure Priorities for EMP and Solar Storms, Security Analysis and Risk Management Association Report, 2011

the electric power system. The grid is essential for sustaining population life-support services such as water and food supply, and electricity is needed to restore other failed infrastructures.

The electric power system operation is brittle and binary - it fails fast and hard, and grid restoration requires significant effort and time. Some essential heavy-duty electric power grid components take months to replace – or years if large numbers are damaged. A primary example is high voltage transformers, which are known to irreparably fail during major solar storms and are thus likely to fail during an EMP event. Protection of these large transformers will buy valuable time in restoring the grid and the lifeline services it enables. By contrast, communications networks are more malleable due to their technological diversity and the relative ease of component replacement and repair.

Electric power grid system protection priorities should start with major grid communication and control facilities to enable situational awareness of system blackout locations and coordinate the grid restoration process. The next order of priority should be protection of blackstart generation plants and power plants supplying power for coolant flow and restart of nuclear power plants to avoid Fukushima-like disasters. Protection efforts must address the generators themselves, generator station step-up (GSU) transformers and associated industrial control systems (ICS) since E1 can damage generator startup and ICS electronics. Protection of transmission systems is the next priority. Transformers can be damaged by EMP or solar GMD effects if not protected. Delivery time for a single large transformer today is typically one year.[7] There are roughly 2,000 large transformers in use in the transmission system today operating at 345 kV and above with many more at lesser voltages.[8] Remaining, non-blackstart generation plants should be protected based on the priority of the infrastructures they serve. Finally, local distribution networks should be protected based on established community and/or utility priorities.[9]

Regarding setting priorities, we have much to learn from the DoD experience beginning in the 1960s until today. The DoD has prioritized and has protected selected systems against EMP (and, by similitude to E3, GMD effects). DoD places emphasis on protecting its strategic weapons triad and associated command, control, communications, computer, and intelligence (C^4I) systems.

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[7] Chris Beck, The International E-Pro™ Report, International Electric Grid Protection, April 2013

[8] James Gilbert, John Kappenman, William Radasky and Edward Savage, The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid, Oak Ridge Nation Laboratory, Metatech Corporation, January 2010.

[9] Mary Lasky, William Harris, Steve Volandt, Powering Through: From Fragile Infrastructures to Community Resilience, INFRAGARD EMP Special Interest Group, December 2016.

Reasons for Lack of Progress

Although DoD has been successful in protecting its high priority systems dating back to the Minuteman system procurement in the 1960s, our civilian enterprise remains unprotected. The lack of progress in protecting the power grid and other critical civilian infrastructures to EMP is due to three main factors:[10]

1. There are prevalent misconceptions about EMP and GMD threats and consequences.

2. Stakeholders are reluctant to act.

3. No single organization is the designated executive agent.

These three factors are addressed in order below:

EMP Misconceptions

There are many misconceptions about EMP that are circulating among both technical and policy experts, in press reports, on preparedness websites, and even embedded in technical journals. Because many aspects of the EMP fields and system interaction physics are non-intuitive, misconceptions are inevitable. Uneasiness about the wide-area, ubiquitous effects of EMP and the diversity of systems affected make it convenient to adopt misconceptions that avoid the need for action. Denying the seriousness of the effect appears perfectly responsible to many stakeholder groups. Misconceptions involving consequence minimization or hyperbole have served to deter action in the past. Downplaying the threats places EMP preparedness on the back-burner compared to other effects. Exaggeration of the threats causes policy-makers to dismiss arguments, ascribing them to tin foil hat conspiracy theories.

Perhaps the most harmful misconceptions include:

1. Nuclear EMP will burn out every exposed electronic system.
2. Alternatively, EMP effects will be very limited and only result in "nuisance" effects in critical infrastructure systems.
3. Megaton class weapons are needed to cause any serious EMP effects – low yield, "entry-level" weapons will not cause serious EMP effects.
4. To protect our critical national infrastructure against EMP and GMD would cost a large fraction of the GNP

[10] G. H. Baker, Testimony before the House Committee on National Security and the House Committee on Oversight and Government Reform, May 2015

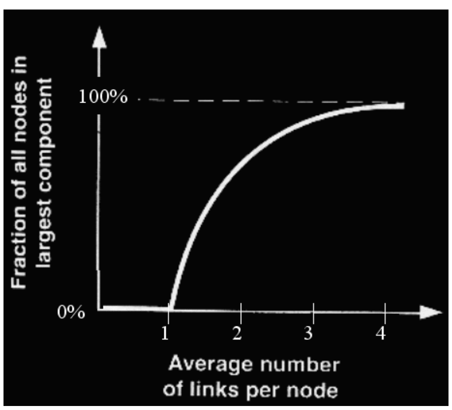
Misconception A: Nuclear EMP will Burn Out Every Exposed Electronic System.

Based on DoD and the Congressional EMP Commission's EMP test data bases we know that smaller, self-contained systems that are not connected to long-lines tend not to be affected by EMP fields. Examples of such systems include vehicles, hand-held radios, and disconnected portable generators. If there is an effect on these systems, it is more often a temporary upset rather than component burnout.

On the other hand, threat-level EMP testing also reveals that systems connected to long lines are highly vulnerable to component damage, necessitating repair or replacement. Because the strength of EMP fields is measured in volts per meter, to first order, the longer the line, the more EMP energy will be coupled into the system and the higher the probability of EMP damage. Because of their organic long lines, the electrical power grid network and long-haul landline communication systems are almost certain to experience component damage when exposed to EMP with cascading effects to most other (dependent) infrastructure systems.

Misconception B: EMP Effects Will Be Very Limited and Cause Only Easily Recoverable "Nuisance" Type Effects in Critical Infrastructure Systems.

Although EMP does not affect every system, widespread failure of limited numbers of systems will cause large-scale cascading failures of critical infrastructure systems and system networks because of the interdependencies among the failed subsystems and the interlinked electrical/electronic systems not directly affected by the EMP.



Paul Erdos' "small world" network theory applies to EMP failure analysis.[11] The graph above illustrates that the average fraction of nodes in any network that are connected to any single network node changes suddenly when the average number of links per node exceeds one. For example, a failed node, where the average links per node is 2, can affect ~ 50% of the remaining network nodes.

[11] Duncan Watts, Six Degrees: The Science of the Connected Age, 2004.

Moreover, for many systems, especially computer-controlled machinery and unmanned systems, upset is tantamount to permanent damage – and may cause permanent damage including structural damage in some cases, to systems due to interruption of control. Examples include:

1. Upset of generator controls in electric power plants

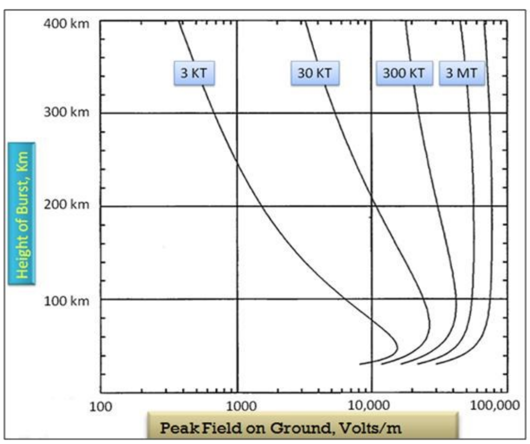
2. Upset of robotic machine process controllers in manufacturing plants

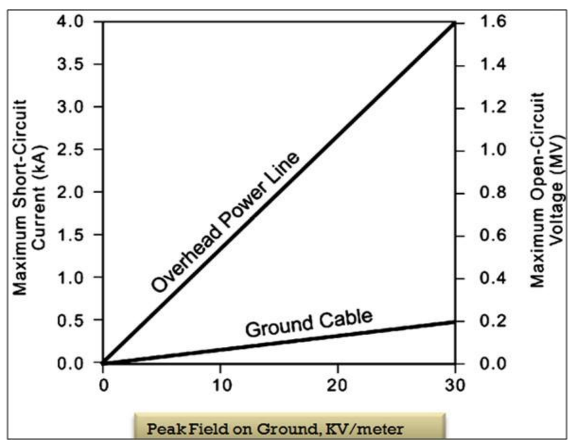
3. Lockup (and the need for reboot) of long-haul communication repeaters

4. Upset of remote pipeline pressure control SCADA systems

Misconception C: Megaton-class nuclear weapons are required to cause serious EMP effects. “Entry-level,” kiloton-class weapons will not produce serious effects.

Due to a limiting atmospheric saturation effect in the EMP generation process, low yield weapons produce peak E1 fields of the same order of magnitude as large yield weapons if they are detonated at altitudes in the 50-80 km range.[12] The advantage of high yield weapons is that their field on the ground is attenuated less significantly at larger heights of burst (that expose larger areas of the Earth’s surface).





The first graph above illustrates that nominal weapons with yields ranging from 3 kilotons to 3 megatons (a 3 order of magnitude difference in yield), exhibit a range of peak E1 fields on the ground with only a factor of 3 difference, i.e. 15kV/meter vs. 50 kV/meter. Although E3 fields vs. yield and height of burst are not illustrated above, a 30 kiloton nuclear weapon detonated

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[12] K.S. Smith, W.A. Radasky, K.J. Mallen, Numerical Fits for Estimating High-Altitude EMP from Unclassified Gamma Ray Pulse Sources, Metatech Technical Note, June 1990.

above 100 km can cause magnetic field disturbances as large as solar superstorms, although over smaller regions.

The second graph indicates that megavolt level and kiloampere-level currents are induced in long overhead lines by E1 from kiloton-class weapons, such as those that might be produced by an emerging nuclear power.

Misconception D: to protect our critical national infrastructure against EMP would cost a large fraction of the U.S. Gross National Product.

Among the critical infrastructure sectors, EMP risk is highest for the electric power grid and telecommunication grids – attention to these infrastructures alone would bring major benefits to national resiliency and enhance deterrent effects. These infrastructures are the most vulnerable due to their organic long lines, and they are also the most critical to the operation and recovery of the other critical infrastructure sectors. As mentioned previously, if we have to pick one infrastructure to protect, the top choice would be the electric power grid.

The Foundation for Resilient Societies, a non-profit organization on which I serve as a member of the Board of Directors, has developed a comprehensive cost estimate for grid protection that includes costs for protecting the grid and the portions of other sectors required for grid operation, viz. fuel supply and communication. Resiliency of the electric grid depends upon concurrent protection of key telecommunications, Class 1 railroad systems that transport coal to generation plants, and interstate natural gas pipeline systems. The combined costs, summarized here, are in the range of $30 billion.

The costs to protect roughly the transmission and distribution system and half of the U.S. generation capacity are provided in the table below:

Resilient Societies EMP Protection Cost Projections

Electric Generation Plants	$23,0000M
Electricity Transmission & Distribution	$2,300M
Electric Grid Control Centers	$1,390.M
Telecommunications	$1,480M
Natural Gas System	$640M
Railroads	$1,380M
Blackstart Plant Resiliency	$80M
	$30,270M

Using the $30,270 bottom line EMP protection cost estimate and a levelized annual revenue requirement of 20% ($6B), assuming there are ~150 million rate payers in the United States, the estimated annual cost per rate payer would be $3.30 per month.

There are strong arguments for protecting selected subsets of the grid. For example, a top priority to ensure situational awareness following an EMP event would be to protect major grid control centers. Estimates to protect these are in the $1.4 billion ballpark. If a Phase 1 EMP program operated in 2016-2020 at a five-year cost of $1.4 billion, or $280 million per year, and all the extra costs were passed through to retail customers, the extra cost would be approximately $0.16 per electric customer per month.

We also might put priority on ensuring the survivability of major grid components that would take months to replace – or years if large numbers suffer damage. A primary example would be high-voltage transformers which are known to irreparably fail during major solar storms and are thus also vulnerable to failure during an EMP event. Protection of these large transformers would save valuable time in restoring the grid and the life-support services it enables. The unit cost for HV transformer protection is estimated to be $350,000. The total number of susceptible units range from 300 – 3,000 (further assessment is required to establish an exact number). Doing the math, the protected cost for protecting 3,000 of these longest replacement lead-time components of the grid is roughly $ 1 billion – a small fraction of the value of losses (Lloyds of London estimates are in the trillions of dollars[13] for GMD alone) and long-term recovery costs should they fail.

Stakeholder Reluctance.

Concern about costs and liabilities makes stakeholders in government and the private sector reluctant to admit vulnerabilities. A major impediment to action on protecting the grid against EMP effects has been that government and industry are (understandably) swayed by the familiar, the convenient, and the bottom line. Like it or not, familiarity and profitability are the touchstones of acceptability – strategic advantage goes to the convenient. Thus, the tendency exists to downplay the likelihood of EMP and any serious associated consequences. The prevalent misconceptions (factor one) have also contributed to stakeholders' ability to downplay the seriousness of EMP effects to avoid action.

In cases where stakeholders have decided to act to improve infrastructure survivability, the actions have been limited and ineffective. A primary case in point is the NERC effort to set reliability standards for wide-area electromagnetic effects. Responding to FERC's inquiries for protection standards, NERC formed a GMD task force. When several task force participants

[13] Space Weather: It's Impact on Earth and Implications for Business, Lloyds of London, 2010. In this report Lloyds advocates development of robust systems designed to operate through space weather events.

asked why EMP could not be part of the task force deliberations, NERC leadership explained that EMP was a national defense concern and therefore not their responsibility – rather that DoD should take the lead. NERC, in their recently adopted EOP-010-01-1 and TPL-007-1 standards, includes a set of operational procedures to protect the electric grid and a scientifically-flawed benchmark GMD threat description that enables most U.S. utilities to avert installing physical protection based on their own paper modeling studies. A skeptic might suspect that the NERC standard's main objective was to avert liability rather than protect the public from serious consequences from wide-area electromagnetic threats.

The outcome of the NERC operational procedures standard, now approved by FERC, is that the public will not be protected from EMP and the industry will deal with GMD effects using operational work-around procedures such as shedding load and spinning up reserve generation capacity that would be useless against EMP given that EMP attacks can occur without warning.

The GMD operational procedures and solar storm benchmark event approved by FERC are ineffective and allow the electric power industry to continue with no significant upgrades to their physical assets, leaving the grid vulnerable to 100 year solar superstorms and EMP. It is worth noting that while GMD fields are more intense at northern latitudes, E3 fields increase at more southerly latitudes relative to the locus of a high altitude EMP event. Utilities that require no protection against GMD because of their southerly latitude under the newly operative standard would be experience higher E3 fields in the event of an EMP event than their northerly counterparts. Further complicating the problem, E3 fields can reach amplitudes an order of magnitude higher than GMD benchmarks. The bifurcated "stove-pipe" threat approach being pursued to protect the electric power grid is cost- and outcome-ineffective. We need to develop a unified, all-threat approach to this challenge which leads to the third and final impediment to progress:

There is No One in Charge.

To a major extent, the lack of progress in protecting our most critical infrastructure to EMP and GMD is that the responsibility is distributed. There is no single point of responsibility to develop and implement a national protection plan. Nobody is in charge. North American Electrical Reliability Corporation representatives maintain that EMP protection should be addressed by DoD. The DoD points to DHS as responsible for EMP protection of the civilian infrastructure. DHS explains that electric power grid EMP protection belongs DOE since they are the designated Sector Specific Agency (SSA) for the energy infrastructure.

EMP protection has become a finger pointing, 'duck-and-cover' game. Our bureaucracy has enabled gaps for addressing the difficult problems of EMP, resulting in no substantive action to protect the nation. We have the classic Washington problem of issues that span departments or fall between departments, which we're all very familiar with, but then we add to that the involvement of the private sector, without central leadership, we're foundering. Because these catastrophes can be continental in scale with everyone in trouble, and there's nobody left to help, the ultimate solution, by default, has fallen to the state and local levels. States are entitled to protect the safety, reliability and adequacy of their electric grids, but most states expect the federal government to provide leadership in protecting the bulk power system. Local level preparedness is crucial, but we still need federal top down guidance to achieve a uniform, coordinated approach to the problem – to be able to triage, to standardize protection methods across the states and localities. We know that we can't protect everything. Uniform guidance is needed to determine what needs to be protected and assign responsibilities. Local jurisdictions need top-level guidance and information to understand what to do.

The current state of EMP protection is random, disoriented and uncoordinated. As we go forward, Congress should establish a responsible party or agency to be the central whip for EMP preparedness. Single POC responsibility and oversight would change the landscape materially and make progress possible.

Recommendations for Future Progress

We must come to grips as a nation with the EMP/GMD preparedness challenges.[14,15] The consequences of these threats are preventable. The good news is that the engineering tools are available to protect a meaningful set of high-priority infrastructures.[16] There are several initiatives that would greatly aid in this endeavor.

First, a designated national executive agency and director is needed. DHS and DoD are likely candidates. Of these, DoD has the most experience. The first order of business should be a national EMP/GMD protection plan and a set of national planning scenarios.

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[14] G. H. Baker, Testimony before the House Committee on National Security and the House Committee on Oversight and Government Reform, May 2015

[15] MIL-STD-188-125-1, High-Altitude EMP Protection for Fixed Ground-Based Facilities, 2005, U.S. Department of Defense

[16] Electric Infrastructure Protection (E-PRO) Handbook, Electric Infrastructure Security (EIS) Council, 2014

enforce regulations, similar to the Nuclear Regulatory Commission. The present FERC-NERC arrangement has proven ineffective with respect to EMP/GMD preparedness.

Background on the Foundation Resilient Societies

The Foundation for Resilient Societies is a non-profit dedicated to cost-effective protection of critical infrastructures from infrequently occurring natural and man-made disasters. Resilient Societies is the only non-profit that consistently participates in FERC rulemakings for grid security standards. We have taken the lead in preparing cost estimates for EMP protection, an essential precondition for state and federal legislation. Our staff overlaps with the Congressional EMP Commission. For more information, see our website at *www.resilientsocieties.org*.

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   James Gilbert, John Kappenman, William Radasky and Edward Savage, The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid, Oak Ridge Nation Laboratory, Metatech Corporation, January 2010.
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