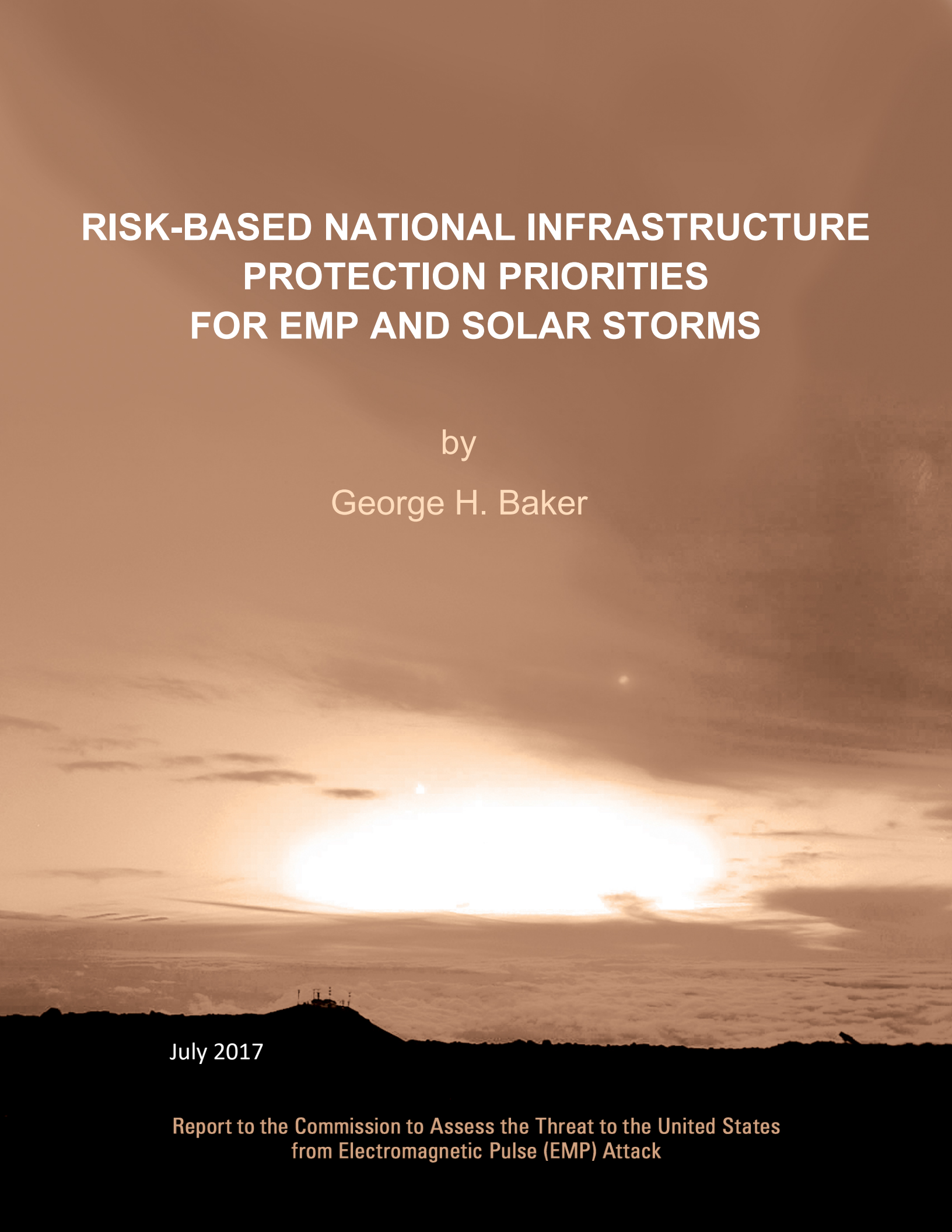


RISK-BASED NATIONAL INFRASTRUCTURE PROTECTION PRIORITIES FOR EMP AND SOLAR STORMS

by

George H. Baker

July 2017

Report to the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack

REPORT TO THE COMMISSION TO ASSESS THE THREAT TO THE UNITED STATES FROM ELECTROMAGNETIC PULSE (EMP) ATTACK

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The cover photo depicts Fishbowl Starfish Prime at 0 to 15 seconds from Maui Station in July 1962, courtesy of Los Alamos National Laboratory.

This report is a product of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. The Commission was established by Congress in the FY2001 National Defense Authorization Act, Title XIV, and was continued per the FY2016 National Defense Authorization Act, Section 1089.

The Commission completed its information-gathering in June 2017. The report was cleared for open publication by the DoD Office of Prepublication and Security Review on June 5, 2018.

This report is unclassified and cleared for public release.

Acronyms and Abbreviations

EMP	electromagnetic pulse
GMD	geomagnetic disturbances
GPS	global positioning system
HF	high frequency
MHD	magnetohydrodynamic
MOV	metal-oxide varistor
UHF	ultra high frequency
VHF	very high frequency

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Introduction

The Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack has provided a compelling case for protecting civilian infrastructure against the effects of EMP and geomagnetic disturbances (GMDs) caused by severe solar storms. Similar to protecting critical infrastructure against any hazard, it will be important to take a risk-based priority approach for these two electromagnetic threats, recognizing that it will be fiscally impracticable to protect everything. In this regard, EMP and solar storms are particularly challenging in that they interfere with electrical and electronic data, control, transmission, and communication systems organic to nearly all infrastructures, simultaneously, over wide areas. The affected geographies may be continental in scale. These events thus represent a class of high-consequence disasters that is unique in coverage and ubiquitous system debilitation. Such disasters deserve particular attention with regard to preparedness and recovery since assistance from non-affected regions of the nation could be scarce or nonexistent. At first blush, the problem of where to begin in developing a national protection program seems overwhelming. Despite the challenges posed by such an endeavor, it is the purpose of the present work to suggest that such a program is possible and affordable based on a system priority approach.

Wide-Area Electromagnetic Environments

The nuclear electromagnetic pulse (EMP), results from a detonation high above the tropopause. Solar storm GMDs occur naturally when an intense wave of charged particles from the sun perturbs the earth's magnetic field.

In the case of high altitude nuclear bursts, three main phenomena come into play, each with distinct associated system effects:

- The first, a "prompt" 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. E1's broad-band power spectrum (frequency content in the 10s – 100s of 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 1000s of amperes. Exposed systems may be upset or permanently damaged.
- The second phenomenon, late-time EMP, also referred to as magnetohydrodynamic (MHD) EMP or 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 100s-1000s of amperes in long conducting lines (a few kilometers or greater) that damage components of the electric power grid itself as well as connected 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.
- The third phenomenon, referred to as the "atmospheric effect" is caused by ionization of the upper atmosphere leading to interference with normal radio wave propagation and

reflection behavior. The interference last for tens of hours and is most pronounced in the HF, VHF, UHF and GPS transmission bands.

Solar storm GMD effects are the result of large excursions in the flux levels of charged particles from the Sun and their interactions with the Earth's magnetic field and upper atmosphere. Two effects are present:

- Perturbation of the Earth's magnetic field, similar to MHD EMP, that generates overvoltages in long-line systems over large regions of the earth's surface affecting electric power and communication transmission networks.
- Ionization of the upper atmosphere, similar to MHD EMP, leading to interference with high frequency (HF), very high frequency (VHF), ultra high frequency (UHF), and global positioning system (GPS) signals. For typical solar storms, these effects last for around 30 hours.

Wide-Area Electromagnetic Infrastructure Effects

Wide-area electromagnetic system effects are challenging due to their near-simultaneous initial effects and cascading effects on a wide array of infrastructures. Infrastructure systems comprised of long-line conductor networks are the most vulnerable to both effects. Susceptible networks include the electric power grid, land-line communications, and interstate pipelines. Effects on these networks will cascade to most other infrastructures. Smaller, self-contained, self-powered infrastructure systems (e.g. hand-held radios and vehicles) are also vulnerable, but only to EMP and to a lesser degree than long-line networks.

Figure 1 provides a summary of the environments, initially-affected systems and effect longevity. Note that significant synergies exist between the high altitude nuclear burst and solar tsunami geomagnetic and ionospheric environments and system effects. Properly designed high-altitude burst protection measures will suffice against solar storms. The converse is not true, due to the E1 effect.

The Congressional EMP Commission has made a compelling case for protection of critical infrastructure.[1] Its conclusions and recommendations apply to both nuclear and solar effects. However, because their charter forced a broad approach, the Commission wrestled with focus. While recognizing the impossibility of protecting all exposed critical infrastructures, the Commission report was not prescriptive in terms of protection priorities. One reason why a U.S. protection program has yet to be initiated is that policy makers continue to wrestle with the question of where to begin, given the long list of critical infrastructure sectors, viz. Agriculture and Food, Water, Public Health, Energy, Transportation, Banking and Finance, Chemical Industry, Emergency Services, Information and Communication, Postal and Shipping, Government Services, the Defense Industrial Base, and Critical Manufacturing.

EMP and Solar Storm Risks

The Department of Homeland Security (DHS) is pursuing a "risk-based" prioritization approach in developing general protection programs. Such an approach is helpful in developing an EMP/Solar Storm threat protection program as well. A commonly used equation for calculating risk is:

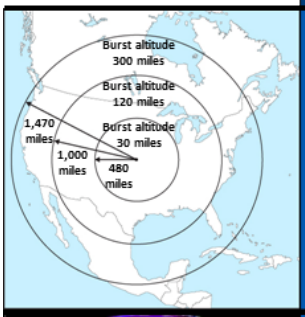
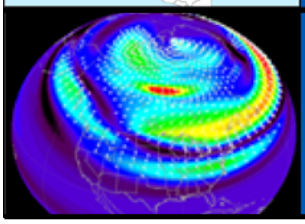
	THREAT	Environments	Susceptible Systems	Effects/ Duration
	High Altitude Nuclear Burst	Gamma-induced EMP (E1)	All electrical, electronic systems	Component damage / indefinite
		Magnetohydrodynamic (MHD) EMP (E3)	Long-line network systems, e.g., electric power grid, terrestrial comm. lines, pipelines	Component damage / indefinite
		Ionosphere electrical properties perturbation	Radio communication systems and GPS	Wave path degradation / 10s of hours
	Solar Tsunamis	Geomagnetic perturbation (GMP)	Long-line network systems, e.g., electric power grid, terrestrial comm. lines, pipelines	Component damage / indefinite
		Ionosphere electrical properties perturbation	Radio communication systems and GPS	Wave path degradation / 10s of hours

Figure 1 Wide-Area Electromagnetic Effects

[1] W. Graham et al., Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, Volume 1: Executive Report, 2004.

$$Risk = E \cdot V \cdot C$$

where E represents probability of system exposure to the threat, V represents system vulnerability, and C represents system criticality. The EMP/solar storm 'exposure factor' is similar for all civilian infrastructures due to the effects' seamless continental-scale coverage. Thus, for the wide-area electromagnetic threats, the equation is simplified because 'vulnerability' and 'criticality' are the sole determinant factors for risk.

A simple risk-based prioritization exercise conducted by the author is instructive using the following vulnerability and criticality criteria:

- EMP/Solar Storm Vulnerability Criteria (V)
  - Does the infrastructure function require connection to long conducting lines and/or networks?
  - Does the infrastructure depend on digital electronic control systems?
  - Are manual work-around procedures available to perform the infrastructure's function?
  - What is the time needed to reconstitute the system?
  - How difficult is it to protect the system?
- EMP/Solar Storm Criticality Criteria (C)
  - How many other infrastructures would fail should this infrastructure be debilitated?
  - What is the immediacy of effects on services provided?
  - How many human casualties would occur?
  - How big is the economic impact?
  - Is this infrastructure necessary to enable the repair and recovery of other infrastructures post-attack?

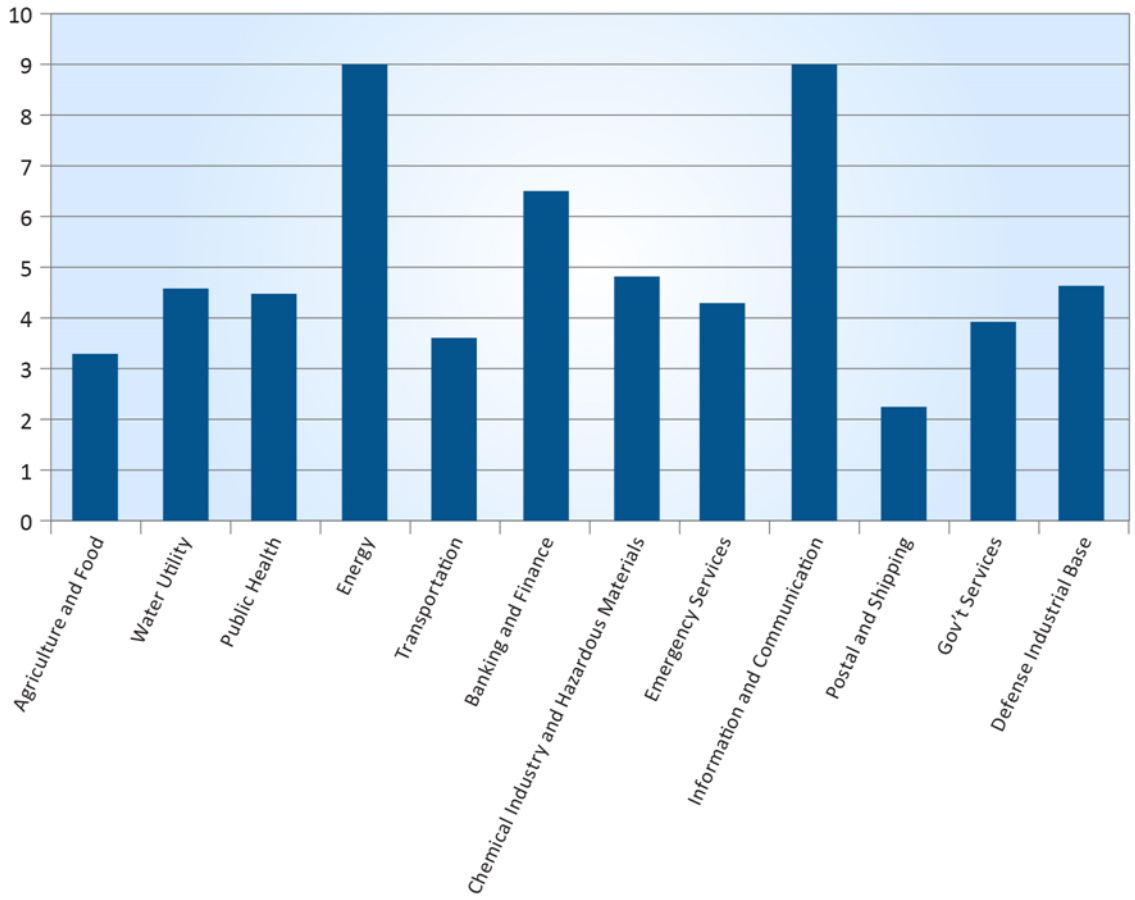


Figure 2 EMP/Solar Storm Risk-Priority Values for Critical Infrastructures

The exercise used a scale of 1 to 3 to score the overall vulnerability and criticality of each infrastructure sector, with 3 being the most vulnerable or critical and 1 being the least. The risk product values thus ranged from 1 to 9. Figure 2 plots the results.

The electric power portion of the energy infrastructure and the information/ communication infrastructure pose the highest risks to society in EMP/Solar Storm scenarios. These infrastructures are the most vulnerable to the wide-area electromagnetic threats due to their organic long-line networks and large associated coupling cross sections. They are the most critical because they enable the operation of all other infrastructures and they are essential with respect to the reconstitution timeline. A profound result of this simple exercise is that our most critical infrastructures are also the most vulnerable to EMP/Solar Storm threats. This conclusion adds impetus for action to protect our electric power and information/communication networks.

Countermeasures

By way of encouragement, we know how to protect systems against wide-area electromagnetic effects. EMP protection has been implemented and standardized by the U.S. Department of Defense

on a host of systems. Because of their northerly latitudes, the electric industry in Great Britain, Canada, and the Scandinavian countries have experienced severe solar storm effects and have developed countermeasures that appear to be effective.

Recognizing that significant portions of the U.S. grid are likely to fail in an EMP or major solar storm event, it will be important to expand provision of back-up power systems for basic life functions. This is a lesson learned from our Hurricane Katrina experience now emphasized by LTG Russel Honoré.[2] Many medical, communication, and financial facilities now have emergency generators. Additional provision of emergency generators is needed for water supply systems, gas stations, food stores, and pharmacies. Emergency generators' protection is relatively easy to implement and certify via test.

We have empirical evidence that EMP and solar storm currents damage transformers within the electric grid. These components are expensive, difficult to move, and the largest of transformers are no longer manufactured in the U.S., requiring months to years to replace. Installation of blocking devices in the neutral to ground connections of transformers will significantly reduce the probability of damage from solar storms and MHD EMP. E1 overvoltage protection is achievable by installing common metal-oxide varistors (MOVs) on transformer terminals. Estimates for protecting the most difficult to replace transformers (transmission grid transformers) in the U.S. range $1 to $10 billion.

EMP protection methods for communication facilities have been developed and implemented by DoD since the 1960s and are well documented.[3] Techniques are applicable for both telecommunications facilities and power grid supervisory control and data acquisition (SCADA) systems. Engineering approaches include use of shielded enclosures, provision of backup power, standard grounding techniques, installation of overvoltage protection devices and filters on penetrating conductors, and intentional cable management. The cost of EMP protection for communication facilities ranges 2 to 5 percent of the building costs if incorporated in the initial facility design. Emergency communication facilities are a good place to start to demonstrate the feasibility and cost-effectiveness of electromagnetic protection. Including EMP/solar storm protection in fire codes and interoperable communication system procurements and related DHS grants would be helpful.[4]

Summary and Future Directions

The huge geographic coverage and ubiquitous system effects of EMP and major solar storms beg the question of "where to begin?" a national protection program. We must be clever in deciding where to invest limited resources. Based on simple risk analysis, the electric power and

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2 G. Baker and C. Elliott, editors. Cascading Infrastructure Failures: Avoidance and response, Homeland Security Symposium Proceedings, James Madison University and Federal Facilities Council, May 16, 2007, pp. 19-31.

3 High Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based C4I Facilities Performing Critical, Time-Urgent Missions, MIL-STD-188-125-1, Fixed Facilities, April 7, 2005 and MIL-STD-188-125-2, Transportable Facilities, March 3, 1999; also MIL-HDBK-423.

4 See National Fire Protection Association. NFPA 1221, "Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems," and NFPA 1600, "Standard on Disaster/Emergency Management and Business Continuity/Continuity of Operations Programs."

communication infrastructures emerge as both the most vulnerable to EMP and the most critical infrastructures, and thus the highest priority for EMP/solar storm protection. Protection of a limited set of high risk infrastructures will go a long way in lessening the societal impact. In the case of electric power, protecting the large distribution transformers and expanding the provision of emergency generators for critical systems will improve the survivability of multiple other interdependent infrastructures. For communication systems, protection of emergency communication centers and interoperable mobile and handheld communication systems are useful first steps. Pilot programs to demonstrate wide-area EM protection engineering for the highest risk infrastructures would pave the way for a comprehensive effort to address critical national infrastructures. Recent Congressional, FERC, and NERC initiatives will hopefully spur progress in this direction.[5,6,7]

[5] H.R. 668, the Secure High Secure High-voltage Infrastructure for Electricity from Lethal Damage (SHIELD) Act, introduced February 16, 2011.

[6] U.S. Department of Energy and the North American Electric Reliability Corporation. *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System: A jointly-commissioned summary report of the North American Electric Reliability Corporation and the U.S. Department of Energy's November 2009 Workshop*, June 2010.

[7] National Academies Press. *Severe Space Weather Events: Understanding societal and economic impacts: A workshop report*, 2008.