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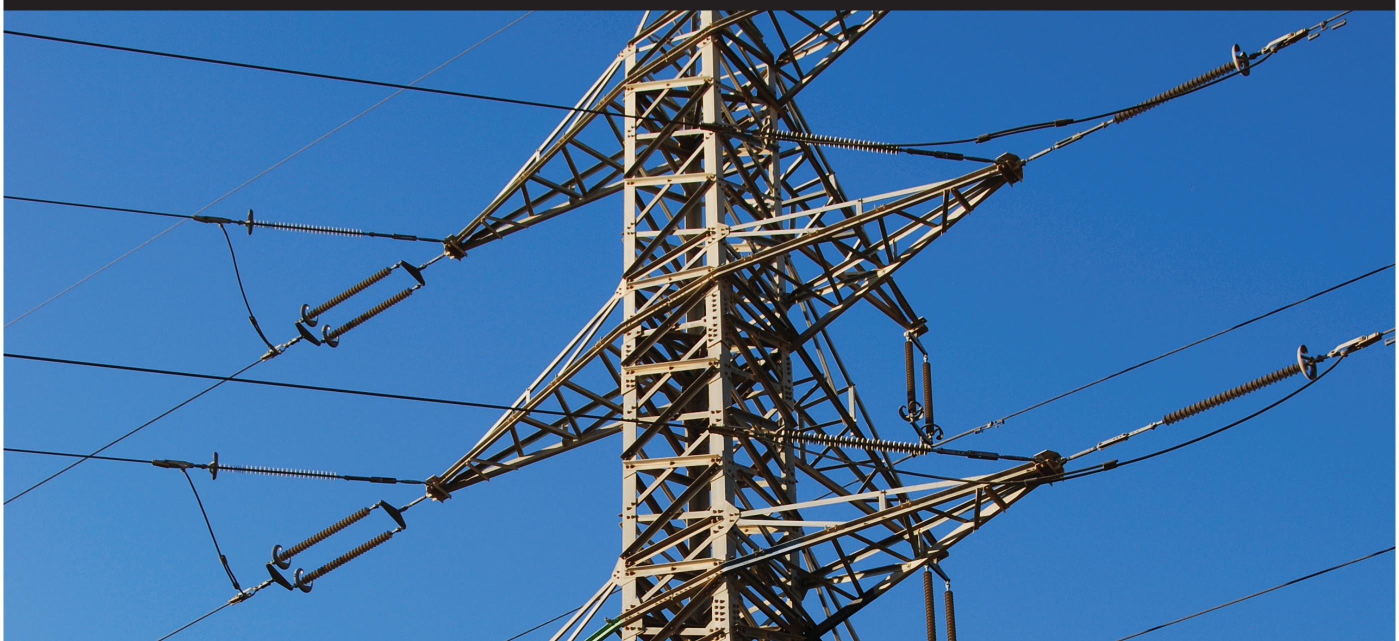
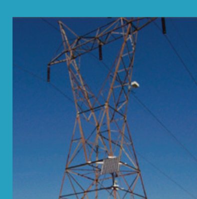
ELECTROMAGNETIC PULSE (EMP) AND THE POWER GRID





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Executive Summary

This EPRI white paper provides background and an introduction to the topic of electromagnetic pulse (EMP, including high-altitude EMP or HEMP) for stakeholders concerned about potential damage to power grid infrastructures. This white paper is the first in a series of papers that address the potential impacts of – and mitigation strategies for – various types of high-impact, low frequency (HILF) events. Though rare, such events – which can include HEMP, geomagnetic disturbances (GMDs), coordinated physical and cyber attacks, pandemics, and others – can potentially result in high costs and damage to the critical electric power infrastructure. Separate white papers cover risk management strategies for HILF events [1], potential application of such strategies to GMDs [2], and a project that EPRI and the U.S. Department of Homeland Security (DHS) are conducting to enhance HILF preparedness (the Recovery Transformer project) [3].

EMP refers to a very intense pulse of electromagnetic energy, typically caused by detonation of a nuclear or other high-energy explosive device. HEMP is an EMP detonated at high altitude to produce more widespread effects (an EMP, as opposed to a HEMP, can cause more localized but still significant impacts). The HEMP from a high-yield gamma ray weapon can in principle impact the functionality of power grids, communication infrastructures, computing and electronic processing systems, and ground transportation systems dependent on microprocessors or embedded electrical systems that are susceptible to the disruptive effects of large EM perturbations.

A number of countries have tested and developed EMP-enhanced nuclear devices, including the U.S. and Russia [4]. The U.S. Department of Defense (DoD) has taken the lead in hardening against and mitigating the potential damage of EMP/HEMP attacks to the U.S. military. However, widespread and coordinated research and development on civilian, electric power industry, and commercial protection and mitigation is lacking. Under the guidance of EPRI, the North American Electric Reliability Corporation (NERC), DHS, and other federal and local agencies, programs and research are underway to provide a more comprehensive response plan in the event of an EMP/HEMP emergency.

This white paper summarizes the following:

- *The EMP/HEMP physical characteristics*
- *The potential range of damage an EMP/HEMP event may cause*
- *Private and public agency mitigation against – and recovery from – EMP/HEMP attacks*
- *The potential next steps needed in EMP/HEMP research, mitigation, and recovery*

Introduction

In July of 1962, as a part of its nuclear testing program, the U.S. military detonated a nuclear device 900 miles (1445 km) from Hawaii at an altitude of 250 miles (400 km) over the Pacific Ocean. The blast, dubbed Starfish Prime, besides its bright visibility in Honolulu, knocked out streetlights, damaged a telephone company's microwave link, set off numerous burglar alarms, and reportedly disabled automobiles on the islands (Figure 1). Despite the long distance from the test site, the damage in Hawaii was directly attributable to the EMP that was generated during the nuclear explosion [4, 5].

Figure 1. Starfish Prime as seen from Honolulu, July 9, 1962 [6]

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The 1962 detonation was the first to provide a confirmation in the field of the potential widespread disruption of electrical devices by high altitude nuclear explosions.[1] Enrico Fermi, a member of the pioneering team that developed and tested the first nuclear device, originally predicted EMP effects during nuclear detonations and took measures to shield sensitive instrumentation from its expected effects during early experiments [5].

Based on the impacts of the 1962 blast and subsequent research, scientists determined that the impact area of the EMP is limited to the physical horizon of the Earth in relation to the location of the nuclear detonation [7]. For example, in the case of a ground detonation, the EMP damage radius spreads to the horizon, which is approximately 62 miles (100 km) depending on the topology of the surrounding terrain, as seen from the surface level. However, high altitude detonations, such as the 1962 experiment, provide a far wider horizon for EMP propagation, so that its effects can spread over thousands of miles [8]. Aside from their range and scope, these HEMP events are identical to the surface level ones in terms of basic physical characteristics.

Multi-Pulse EMP Components during Nuclear HEMP Events

Unlike the electromagnetic perturbations created by solar storms interacting with the Earth's magnetosphere (geomagnetic disturbances), the HEMP generated by the detonation of nuclear devices creates a three-component pulse, each with distinct characteristics as defined by the International Electrotechnical Commission (IEC). The commission labeled the sequential components E1, E2, and E3 [9].

E1 Pulse

The first pulse component, E1, generates a brief, yet highly energetic, electromagnetic field that may induce extremely high voltages as it couples with electrically conductive structures. The E1 component is responsible for the most damage in any HEMP event, as the high voltages may cause electrical breakdown in devices and components. The damage or functional disruption occurs practically simultaneously over a very large area [10].

The gamma radiation generated by the high altitude nuclear explosion causes the E1 pulse by dislodging electrons from atoms (the Compton Effect) in the upper atmosphere. The electron trajectories are bent by the Earth's magnetic field to follow a spiral trajectory and as accelerated charged particles they emit EM radiation [11]. Because of these deflections by the magnetosphere, if the blast occurs near the equator, the severity of damage occurs in a roughly symmetrical (circular) pattern. North or south of the equator, these deflections would cause damage in a U-shaped curve (see Figure 2). An E1 pulse lasts approximately 1000 nanoseconds [12].

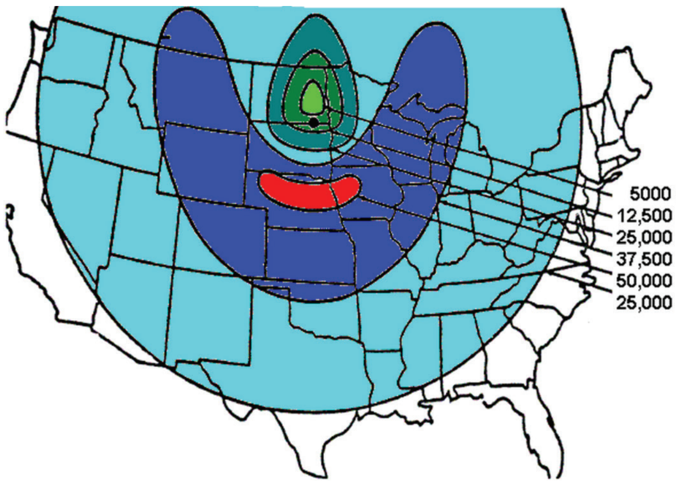

Figure. 2. Wave pattern of HEMP E1 pulse related to curve of Earth's electromagnetic field [13]

E2 Pulse

The E2 pulse produced by HEMP explosions is generated by scattered gammas (secondary gammas) and by "neutron scatter gammas" from gammas created when the neutrons produced by the nuclear weapon are scattered by air. The E2 pulse is similar to a conventional lightning strike, beginning approximately a few microseconds to one full second after the onset of the E1 pulse. Because the EM energy generated by the E2 pulse is not nearly as intense, it is easier to protect against its damage with conventional technology. However, it is possible that following the E1 disruption, the protection systems may have already been compromised. Consequently, the E2 pulse may pass relatively unhindered, affecting components deeper into the electric grid.

[1] *After the Nagasaki and Hiroshima bombings or 1945, neither the Japanese nor U.S. government noted the effects of EMPs.*

E3 Pulse

The E3 component is similar to the geomagnetic disturbances (GMDs) that occur when particles from solar flares strike the Earth's magnetosphere. The E3 results from perturbations of Earth's magnetic field produced by the detonation blast wave. The E3 component, lasting from tens of seconds to minutes in duration, has the potential to impact the operation of power grid transformers, relays, and related control and processing electronics.

Non-Nuclear EMP Attacks

Military agencies have developed high- and low-frequency EMP weapons that induce pulse voltages over limited, targeted strike zones. These weapons, if properly deployed, could cause damage to the electrical grid, command and control communications, transformers (potentially at any voltage level, due to the induced transients on the grid above nominal values), and electronic circuitry. While the effects of non-nuclear EMP attacks are similar in nature to nuclear HEMP events, they cover a much more limited target area.

For the purpose of utilization in the battlefield, these devices attempt to disable enemy communications and transportation. As a means for a widespread attack on a nation's infrastructure, non-nuclear EMP devices are impractical, but they could nonetheless easily target a city, specific generation facilities, or major communication hubs to cause significant, potentially long-lasting, material and economic damage. Because of the relatively simple design of such devices compared to nuclear weapons, it is conceivable that rogue nations or terrorist groups could develop a credible threat based on non-nuclear EMP attacks on a variety of targets.

Potential Destructive Impact and Likelihood of a HEMP Event

- In the event of a high-altitude nuclear explosion, the following factors primarily determine the scope and severity of damage caused by a HEMP:
- The altitude of detonation
- The gamma-yield of the device
- The geographical details of the terrain below the blast
- The distance from the detonation point
- The local strength and direction of the Earth's magnetic field at any location(s) in the blast zone
- The electromagnetic vulnerability of the infrastructure being impacted by the HEMP

Gamma-yield enhanced nuclear weapons generate a larger amount of EM power (compared to the nuclear blast in "standard" designs) and the height of the detonation determines its range of impact. It is reasonable to assume that nations with a long-established nuclear arsenal have already developed and/or partially tested HEMP-enhanced versions of nuclear weapons, which are designed to deliver greater gamma ray output with relatively lower megaton yields. For example, using more efficient chemical explosives to initiate the detonation along with enhanced casing materials can generate a larger amount of gamma radiation leading to a stronger E1 pulse [14].

Furthermore, several nations have the technology know-how to develop non-nuclear EMP devices, along with the capability of unleashing attacks through the use of long-range missiles (that is essential for delivering the EMP payload at high-altitude) [15].

Military and government assessment and quantification of the likelihood of HEMP attacks are incomplete, at least according to the information in the public domain. Due to the technical requirements of developing or obtaining both nuclear weapon capabilities and long-range missile delivery systems, the list of potentially threatening nations is short. Furthermore, the motivation for such an attack is also subject to debate and strongly affected the international political environment. Retaliation in the form of a massive counter-attack may be a sufficient deterrent to a first-strike HEMP launch for a government with vested interests in the international arena, but not for a "rogue nation" or terrorist group: ultimately, the threat does exist, and the studies conducted so far on this matter are sufficient to quantify the effects of a high-altitude, high gamma-yield nuclear explosion with reasonable accuracy [15].

Potential Scope of HEMP Damage

The largest U.S. H-bomb detonation (Starfish, 1962), at an altitude of 250 miles (400 km) had some HEMP impact 800 miles (1445 km) away, on the Hawaiian Islands, but without drastic consequences. However, the explosion occurred over the ocean, and the level of large-scale power grid interconnectivity in the Hawaiian Islands at that time was very limited, compared for example to the northeast region of the U.S. A similar event reaching a densely electrified area would likely have a quite different impact. Although an actual HEMP event is not very probable because it requires a large nuclear bomb and a large missile to reach altitude, a lower altitude "tactical" attack is more plausible (in this case, the affected area would be limited to a line-of-sight radius).

Research and development related to HEMP devices has been focused on producing a HEMP-enhanced nuclear explosion that can cause potential damage over a large land mass. The damaging effects, besides possibly affecting major power grids in large geographical regions, could also include:

- Disruption of cellular wireless communications
- Failure of computer systems
- Disruption of business and financial computing systems
- Depending on the blast intensity and proximity to the blast point, damage or disruption to a significant portion of the transportation infrastructure
- Disruption of non-military grade (unhardened) video, radio, and internet communications
- Interference with air transportation, as unhardened or unprotected critical aircraft instrumentation could lose functionality
- Damage to petroleum and natural gas delivery systems
- Disruption of essential services dependent on the power grid, such as healthcare facilities, waste treatment, and food distribution systems

Military studies have documented the effects of HEMP attacks as observed in the field or through experimental tests. All available studies confirm the likelihood of the above mentioned HEMP effects on unprotected infrastructure systems. In testimony before the U.S. Congress (Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack), for example, military officials have stated that the military facilities are largely prepared and hardened against HEMP disruptions and that equipment and facilities are regularly tested for HEMP vulnerabilities. All critical U.S. military equipment must now conform to the MIL-STD-188-125 standard for mitigating HEMP effects [16]. There are other sectors, for examples aerospace, automotive, financial institutions, and government agencies, where the MIL-STD-188-125 standards have been adopted for hardening systems against EMP attacks.

Potential Power Grid Damage

In a joint report issued in June 2010, the U.S. Department of Energy (DOE) and NERC outlined a number of HEMP vulnerabilities in power grid and power distribution systems [17]. The report, "High-Impact, Low-Frequency Event Risk to the North American Bulk Power System," details vulnerabilities, some of which are summarized in the remainder of this section.

High Voltage Substation Controls and Communications

The coupling of sensors in the transformer to cables inside of control rooms is most vulnerable to HEMP pulses. While a 3.2-kV surge is sufficient to trigger relays, initial maximum HEMP levels of 10 kV could propagate to relays and other electronic controls. A surge as little as 0.6 kV could cause significant damage to PROMs and other microprocessors in computer and embedded system controls, thereby crippling substation operations.

Generation Facilities

Testing at generation facilities has shown that voltages as low as 0.6 kV are sufficient to destroy programmable logic controllers used in the flow of fuel and other power generation processes. In addition, cabling within these facilities is subject to the same inadequate protection as those in substation control and communications.

Control Centers and SCADA

Supervisory Control and Data Acquisition (SCADA) systems in nearly all power grid operations rely heavily on digital control systems (DCS) and programmable logic controllers (PLC) networked together over the grid. SCADA systems resemble the physical architecture of common personal computers, with microprocessors, system bus controllers, and interfaces for communicating with external devices and with other SCADA components. These systems monitor and control the operation of most power systems. In the event of a critical loss of a power generation facility or failure of other major components, the SCADA systems automatically issue alerts and then issue commands to other facilities under their control to remedy the situation, including rerouting power from other systems. Testing reveals that levels as low as 0.6 kV cause significant damage to PC-type components: a large-scale EMP could then disrupt operations of entire centers and inter-center communications, either directly or through cascade-type events [18].

Distribution Lines

According to NERC, approximately 78% of all electric power delivery to end-users passes through medium-voltage (in the 10 kV range) distribution lines. The almost random orientation along the surface of the single-feeder lines increases the potential for worst-case scenario exposure, where some feeder segments would see the maximum E1 HEMP voltage, creating a possible insulator flash-over and system failure. This conclusion was reached by the "EMP Commission on the Threat and Critical National Infrastructure" in the analysis of induced over-voltages ranging from 200 kV to 400 kV over geographically widespread areas, especially for cases where flashovers occur within one mile of a substation with high fault current [18].

Distribution Transformers

Testing at Oak Ridge National Laboratories in the 1980s examined possible E1 pulse damage to step-down transformers. The 19 tests performed found that the systems experienced operational damage during fast-peak pulse simulations in 7.2-kV/25-kVA power distribution systems. The pulses caused pinhole-type damage and dielectric breakdown within the windings in transformers without direct-connected arresters. In general, HEMP attacks could affect step-down transformers and could cause multiple system failures [17]. With protection in place, the risks can be greatly reduced.

Smart Grid Semiconductor Devices

Due to the nature of the E1 component, there is a high probability that affected computing devices, unshielded control devices, and smart grid components not specifically hardened for HEMP events could fail, just as they would in standard computing environments. For example, an EM weapon (specifications are classified) mounted on an unmanned aerial vehicle demonstrated the ability to severely impact a multitude of common electronic devices [19].

Power Grid Support Transportation Systems

Another uncertainty is the extent of damage to transportation systems, such as repair vehicles and diesel/electric locomotives used to service and transport spare transformers or parts and repair crews to HEMP damaged plants. While adequate replacement components may be on hand through advance preparation planning, transportation is essential to quickly and reliably repair equipment and systems in the event of a catastrophic EMP, HEMP, or other HILF events such as GMDs.

Modern cars and trucks in particular contain a significant number of microelectronic components and could experience damage that incapacitates the vehicles if not sufficiently shielded. Independent testing by vehicle manufacturers concerning EMP shielding and protection is not publicly available, although major manufacturers have conducted such tests [20]. The manufacturers will not disclose the results of these tests, nor the model vehicles and/or trucks they have tested. In addition to these vehicles, testing of locomotives may be needed, as the delivery of recovery transformers and repair crews and equipment may rely heavily on railway transportation.

Mitigation and Recovery from HEMP Effects

In the event of a HEMP attack, in order to reduce the number of affected systems, limit the scope of damage, and bring systems and infrastructures back online as soon as possible, the following guidelines should be considered:

1. Early detection and solid response plans are essential to preparedness. While detection or prevention of an attack is beyond the purview of private stakeholders, coordination between the military, the power industry, and other affected agencies and first responders is needed to limit initial damage and initiate procedures for a swift recovery of impacted systems.
2. Broader understanding within the private sector of the potential for HEMP threats should lead to the design of more resilient components and systems. In parallel to the hardening of existing systems, stakeholders should guarantee adequate supplies of spare components and emergency operations procedures.
3. Post-HEMP plans should focus on swift repair, re-supply, and infrastructure recovery, as well as power system-wide coordination, from the national to local levels.

Inter-Agency Cooperation

Inter-agency cooperation is crucial to move forward. For example, NERC is working with the DHS National Cybersecurity and Communications Integration Center. The objective is to develop bi-directional sharing of critical infrastructure protection information between the government and the power industry sector. NERC is also interfacing with the U.S. Northern Command (NORTH-COM) to coordinate electric grid-focused activities, which could include participation in the SecureGrid Exercise to provide electric sector situational awareness. This U.S. private industry/government collaboration could extend to the Joint Capability Technology Demonstration Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS). The focus of SPIDERS is to investigate the development of small, yet reliable, micro-grids on a short-term, emergency basis [21].

Need for Modeling

While individual power grid stakeholders have made strides in the mitigation of potential damage represented by both GMD and HEMP attacks, the report *Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack* states: “No currently available modeling and simulation tools exist that can adequately address the consequences of disruptions and failures occurring simultaneously in different critical infrastructures that are dynamically interdependent. Many infrastructure models that do exist are local to regional in scope.” [18].

Power Grid Hardening and Mitigation

In its 2008 report, the EMP Commission concluded that protecting the entire power grid system, or even all high value components, from HEMP pulse attacks is impractical because the costs, time, and effort in proportion to the likelihood of a HEMP-enhanced nuclear strike make it prohibitively expensive [18]. The report recommendation is to prepare for the widest possible scenarios of GMDs and EMPs with a focus on quick response and repairs, as well as conduct further research into cost-effective mitigation and preparation. Work has already begun in these areas, including efforts outlined in the following subsection.

Shielding of Above Ground Components

The U.S. military, for example, specifically under the MIL-STD-188-125 standard, deploys technology for protecting fixed and mobile installations from EMP effects. Ground-based shielding detailed in MIL-STD-188-125 refers to *“subscriber terminals and data processing centers, transmitting and receiving communications stations and relay facilities for both new construction and retrofit of existing facilities”* (see Figure 3). This standard calls for EMP mitigation for all military command, control, communications, and computer systems, including the EM energy point of entry (POE) to these systems. Adhering to this standard would greatly enhance the protection of North American power grid reliance on its current and future SCADA operations, including smart grid components and systems, but would be extremely costly [16].

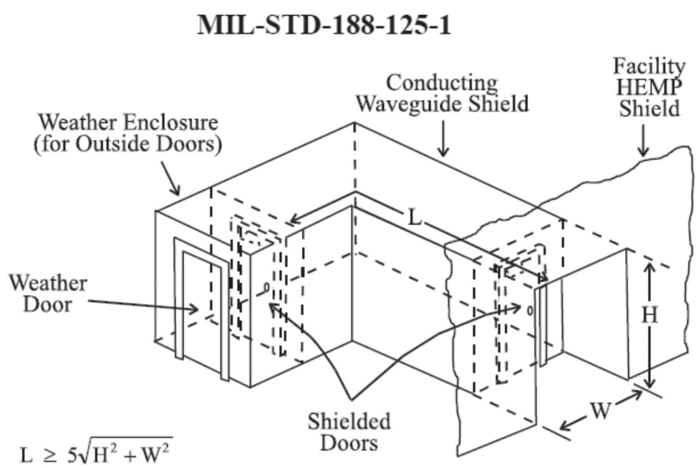

Figure 3. HEMP shielding around control facility [16]

The major requirement of the standard relies on Faraday cage implementation(s) around specific components, POEs, or entire facilities. The cage is composed of conductive mesh materials and an insulation barrier around components or entire facilities that absorb pulse energy and channel it directly to ground. The underlying electrical components enclosed in the cage remain intact and unaffected.

Standby, Backup Power Generation and Transformer Deployment

The design and manufacture of storable and easily transportable backup power generators and transformers is required for restoring HEMP-damaged facilities. Government and power industry stakeholders could warehouse the hardware in hardened and geographically dispersed locations for rapid transport to affected areas to restore power quickly to any section of the grid affected by EMPs or other disasters that may disrupt power delivery.

The main requirements of such systems are the ease of integration into the current power grid; a relatively compact and easily transportable form factor; and sufficient capacity and capabilities to restore reasonable amounts of power until full replacement generators and transformers are available. To demonstrate the technical and economic viability of such an approach, EPRI and DHS have installed a prototype set of three high-voltage "Recovery Transformers" at a host utility [3].

Stored and Shared Spare Components

Another essential component in the recovery process is the availability of components needed in the event of an emergency. These components could be shared among all stakeholders and geographically dispersed for quick access. The industry can assess the vulnerability to EMP exposure of various components and systems and the inventory of available equipment to plan sufficient quantities of backup components where needed. Transformers, generation equipment, SCADA, aboveground relays and controls, and other embedded processors are examples of potential spare part candidates for stockpiling.

The goal of a NERC Spare Equipment Database (SED) program is to provide a means to securely connect entities that need replacement transformers with entities that have such spares available in the event of simultaneous loss of multiple transformers [22]. The Edison Electric Institute's (EEI) Spare Transformer Equipment Program (STEP Program), launched in 2006 in response to the 9/11 terrorist attacks, addresses the need to manage resources in response to a terrorist attack. About 50 transmission providers that represent about 70% of the U.S. transmission grid currently participate in this program [23]. Defined stakeholders could take responsibility for the inventory, research, and securing of hardened facilities for these parts depots, including a coordinated and clear command and distribution network for part deliveries and repairs. Realizing this vision would require cost and feasibility studies, as well as research that identifies the most vulnerable components under different EMP scenarios (the fact that many components are now manufactured overseas should also be taken into account as a further complication).

Existing/Planned Industry-wide Efforts

In NERC's 2010 HILF report, referring to HILF events, NERC states that "NERC and the U.S. DOE will work together with the electric sector, manufacturers, and other government authorities to support the development and execution of a clear and concise action plan to ensure accountability and coordinated action on these issues going forward" [17].

Next Steps

EPRI recommends the framework shown in Figure 4 to guide next research steps in the area of EMPs. The first step is to define EMP characteristics (e.g., gamma yield and altitude of detonation) for further study. The next step is to perform modeling and simulation of the impact of these scenarios on wide area and local power systems. The vulnerability of these power systems should then be assessed, with particular emphasis on the vulnerability of new and emerging smart grid systems. Mitigation is a major area of research, including development of response plans, equipment spares strategies, equipment hardening, and others. Inter-agency cooperation is a key part of this and other recommended research efforts. Risk management involves integrating the assessment and management of risks from EMPs, other HILF threats, and non-HILF threats that utilities face. Methods developed in this process can be refined and improved as more information on scenarios, EMP-generating devices, grid modernization equipment vulnerabilities, and mitigation methods is obtained.

Enhanced communication and education of all stakeholders on specific EMP threats and their impacts is needed for an effective defensive strategy to be set in place. Education efforts could, for example, recommend ways of implementing practical and phased steps in mitigating and recovering from the most likely EMP events.

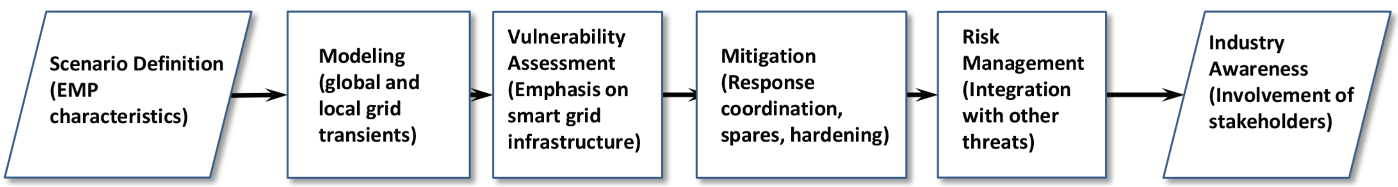

Figure 4. Overview of recommended EMP research activities

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Substations

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