ELECTROMAGNETIC PULSE AND SPACE WEATHER AND THE STRATEGIC THREAT TO AMERICA'S NUCLEAR POWER STATIONS

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The vulnerability of America's nuclear power stations and research reactors to meltdown from electromagnetic pulse (EMP) and space weather (GMD) is one of our most critical national security challenges. In its current state, the United States is not prepared to adequately mitigate or contain an EMP attack or large GMD event. While the probability of EMP or GMD event is low, the ability for either event to impact the nuclear grid and devastate every corner of society and the environment places a very high price on the cost side of the cost-benefit analysis scale.

The Authors are appreciative to the researchers, scholars, experts, and scientists across a range of fields who contributed to this report. We encourage every reader to share this study and its findings to help citizens and leaders to better understand this critical issue and help strengthen America.

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"The opinions and views expressed in this paper are those of the authors alone and do not represent those of the U.S. Government, Department of Defense, Siemens, or Union of Concerned Scientists."

By David J. Stuckenberg* and Hershel C. Campbell**

Abstract

This research addresses a critical information gap by examining technical and security aspects of nuclear plant design, nuclear disasters, the regulatory climate, and how these factors could impact our national security in the wake on an electromagnetic pulse (EMP) or space weather (Geo-magnetic Disturbance -GMD) event. While there are a number of conventional risks to nuclear power stations such as acts of nature, cyber-hacking, and terrorism; EMP and GMD is part of a unique risk set which has the capability of causing systematic wide-spread failures which can lead to simultaneous and catastrophic meltdowns at nuclear power stations and research reactors across the U.S.. To date little research has explored the impact of GMD on nuclear power from a technical and national security perspective; whereas the impact of EMP on nuclear power has not been comprehensively examined in public view for over 30 years.

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Introduction

On June 26, 1954, the world's first nuclear power station, at Obninsk, Russia, began producing electricity for a commercial power grid. Today, more than 438 nuclear power stations operate in 31 countries supplying ten percent of the world's electric power.[1] As global energy demands grow unabated, the nuclear power sector has experienced a renaissance with more than 60 stations in planning or construction to meet long-term needs. Presently one quarter of the world's nuclear power facilities, not including 31 commercial and government research reactors, operate in thirty U.S. states.[2, 3]

During the three decades since the Three Mile Island (TMI) accident in Middletown, PA., the U.S. nuclear industry improved its image and credibility in the near absence of major incidents. It transformed and modernized by merging critical systems and functions with delicate technologies. Despite the transformation, regulations and safety assumptions have remained static since the 1980s. In 2011, after the $122-billion disaster at Japan's Fukushima Daiichi nuclear power station, it became clear long-standing safety and security assumptions within the nuclear industry required re-evaluation.[4] This study evaluates the strategic consequences of man-made and natural forces acting on new technologies regulated by old assumptions.

While most commercial nuclear power station designs presently used are considered safe, an emergent understanding of the effects of Electromagnetic Pulse (EMP) and space weather, or Geo-magnetic Disturbance (GMD), on components and processes such as supervisory control and data acquisition systems (SCADA), large power transformers (LPTs), computer hardware, Emergency Diesel Generators (EDGs), communications and logistics required for the safe operation of nuclear power stations and reactors suggest most designs, regardless of vintage, present a strategic risk to national security from meltdown if severely impacted by these phenomena. The Fukushima disaster, second worst nuclear accident in history, represents a case

[1] *Nuclear Power Plants, World-Wide,* 2015 Eur. Nuclear Soc'y (2015), https://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-world-wide.htm.
[2] Ibid.
[3] Ibid.
[4] Based on Tokyo Power Company (TEPCO) and post incident government figures 2011-2014.

study for what could result, en masse, if U.S. regulators, the utility industry and the national security enterprise fail to adapt to the present threat climate.

Threats posed to the U.S. infrastructure and society from EMP and GMD events remain both a White House and Congressional priority; being addressed in several Congressional research reports (in 2004, 2008, 2009, 2012, 2013, and 2015) and by the Department of Energy (DOE) and Oak Ridge National Laboratory research on GMD (in 2012 and 1991).[5, 6, 7, 8] Numerous books, articles, congressional testimony and public statements by experts like EMP Commission Chairman, Dr. William Graham--all warn about the catastrophic consequences of nuclear reactor vulnerability to EMP.

Yet all have been ignored by the Nuclear Regulatory Commission, which continues to base its policy on an obsolete 1982 NRC study (hereafter the cited as 1982 Christmas Report) that wrongly asserts: "The likelihood that individual components examined will fail is small; therefore, it is unlikely that an EMP event would fail sufficient equipment so as to prevent a safe [cold] shutdown."[9] These findings and others in this vein, are at best, highly questionable and very optimistic. This study examines the 1982 Christmas Report in detail and demonstrates that while its premise was worth exploration; its methodology undermines its validity and applicability in a 21st Century nuclear power industry largely reliant on solid-state silicon devices and semi-conductors.

This study of nuclear reactor vulnerability to natural and manmade EMP--the most in depth unclassified study of its kind--finds that unprotected nuclear reactors pose an existential threat to

[5] Dr. John S. Foster, Jr. et al., 1 Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack (United States Cong. 2004) [hereafter EMP Commission 2004], http://www.empcommission.org/docs/empc_exec_rpt.pdf.
[6] Dr. John S. Foster, Jr. et al., 1 Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack (United States Cong. 2008) [hereafter EMP Commission 2008], http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf (last visited Aug. 8, 2015).
[7] Ostrich, John, DOE/OE GMD Space Weather Program (United States Department of Energy, 2015), p. 2, https://secureweb.inl.gov/gmdworkshop/pres/J_Ostrich_DOE-OEGMDSpaceWeatherProgram.pdf.
[8] Barnes, P.R. et al., Electric Utility Industry Experience with Geomagnetic Disturbances (Oak Ridge National Laboratory), http://web.ornl.gov/~webworks/cpr/v823/rpt/51089.pdf.
[9] David M. Ericson, Jr. et al., 2 Interaction of Electromagnetic Pulse with Commercial Nuclear Power Plant Systems (Sandia Nat'l Laboratories 1983) [hereafter 1982 Christmas Report], http://prod.sandia.gov/techlib/access-control.cgi/1982/822738-2.pdf.

the American people. This study also finds that there is no excuse for nuclear reactor vulnerability to EMP and makes recommendations for correctives.

Key Terms

The following is an overview of important terms used within this study:

CME – CORONAL MASS EJECTION: "A cloud of magnetized solar material that erupts from the sun's atmosphere, the corona, into interplanetary space. CMEs often occur at the same time as flares, and scientists currently study how the two phenomena are connected. At their largest, CMEs can contain 10 billion tons of matter, and they can move at speeds of up to four million miles an hour."[10]

EDG – EMERGENCY DIESEL GENERATOR: Generators used to power nuclear facilities in the event of primary power loss (shut down of the reactor) or loss of power from outside the plant. Most nuclear plants have two or three EDG's per reactor.

EMP – ELECTROMAGNETIC PULSE: A pulse generated from a nuclear explosion that is comprised of three phases - E1, E2, and E3. EMP waves are capable of damaging all electronic devices.

> *E1 – E1 HEMP*: An electromagnetic signal generated by a nuclear burst detonated high above the Earth – generally "above the atmosphere." E1 HEMP is a fast, narrow pulse, typically going up to high electromagnetic field levels not commonly seen from natural events … E1 HEMP is the "prompt gamma signal" part that lasts about a microsecond.[11] Due to their speed and disruptive characteristics, E1 signals are considered one of the more devastating EMP effects on sensitive electronics.
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> *E2 – INTERMEDIATE TIME HEMP:* A signal consisting of an E2A (scattered gamma HEMP) and E2B (neutron gamma HEMP) waves.[12] This signal's effects are similar to lightning when they interact with electronic devices. In some cases, common surge protectors may enable an electronic device to withstand this signal.

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[10] Terms and Acronyms (Nat'l Aeronautics & Space Admin. 2012) [hereafter NASA Terms], http://www.nasa.gov/mission_pages/iris/overview/definitions.html (last visited Aug. 8, 2015).
[11] Edward Savage , James Gilbert & William Radasky , The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid (Metatech 2010), http://web.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-320.pdf (last visited Aug. 8, 2015).
[12] Ibid. 2-7.

E3 – LATE TIME HEMP OR MHD (magnetohydrodynamic) EMP: A signal consisting of E3A (blast wave) and E3B (heave) MHD waves.[13] E3 signals are also produced by GMD events.

GMS/GMD – GEOMAGNETIC STORM OR GEOMAGNETIC DISTURBANCE: The storm and associated disturbances in the Earth's magnetosphere caused by solar wind usually associated with coronal mass ejection (CME) events.[14] GMS or GMD are often interchangeable.

HEMP – HIGH ALTITUDE ELECTROMAGNETIC PULSE: A manmade EMP pulse resulting from a high altitude nuclear detonation designed to maximize a geographic area's exposure to EMP. A HEMP propagates E1 – E3 waves and can be used as an asymmetrical means of attack on an adversary to disable technologies upon which he may rely. **For the purpose of this research, all manmade EMP events will be considered in the context of HEMP events.**

LPT – LARGE POWER TRANSFORMER: Transformers used to push electricity from generation sources over long-distance power transmission lines to substations and end users.[15]

SCADA – SUPERVISORY CONTROL AND DATA ACQUISITION SYSTEMS: The interface between a computer driven command (input) and mechanical function (output) in a control system. SCADA essentially regulate multiple functions in vast electronic networks from communications to power distribution. Modern society is dependent on SCADA devices.

Electromagnetic Pulse and Solar Events

There are several known sources of EMP including nuclear detonations, high or direct energy weapons, and naturally occurring space weather (phenomena created as a bi-product of CME

[13] Edward Savage, James Gilbert & William Radasky , The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid (Metatech 2010), 2-7, http://web.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-320.pdf (last visited Aug. 8, 2015).
[14] Jennifer Rumburg, Solar Storm and Space Weather - Frequently Asked Questions (Nat'l Aeronautics & Space Admin. 2015) [hereafter NASA Solar Storm Q&A], http://www.nasa.gov/mission_pages/sunearth/spaceweather/index.html#q7 (last visited Aug. 8, 2015).
[15] LARGE POWER TRANSFORMERS and the U.S.ELECTRIC GRID (Infrastructure Sec. & Energy Restoration Office of Elec. Delivery & Energy Reliability U.S. Dep't of Energy 2012) [hereafter DOE LPT Report], http://energy.gov/sites/prod/files/Large%20Power%20Transformer%20Study%20-%20June%202012_0.pdf.

interacting with the Earth's magnetic field) and more recently, deliberately developed EMP weapons. Until Cold War nuclear testing, EMP was not well understood outside theory. However, firsthand knowledge was gained in 1960's when the Department of Energy (DOE), Department of Defense (DoD) and partners conducted HEMP testing. Side effects from one of the HEMP pulses caused a partial blackout in Honolulu, HI, stopped vehicles, disrupted radio communications and damaged satellites in low-earth orbit.[16] Notably, many of the effects, including blackout, were observed nearly 1,000 miles from the detonation's epicenter.

With respect to HEMP, a nuclear detonation causes an intense release of gamma-ray radiation. "Through collisions with air molecules, the gamma-rays produce high energy Compton electrons. The Compton electron currents interact with the Earth's magnetic field, thereby generating electromagnetic fields that propagate (toward the surface) as a coherent pulse of electromagnetic energy."[17] This energy interacts with conductive surfaces such as power lines, transformers, electronic devices and other highly conductive surfaces.[18] The waves generated by HEMP are primarily E1 and E2, with a much lower E3 impact. The effects of HEMP and the resultant waves are well understood and are considered by many adversaries to be a highly effective means of asymmetric attack against the U.S.. In some cases, adversarial planning options consider delivery and detonation of a single nuclear weapon at high altitude above the Continental U.S. (CONUS). While such a detonation would have little to no kinetic damage, as seen at Hiroshima or Nagasaki, the resultant HEMP would cripple most unprotected technologies reliant on electricity and semi-conductors (Figure 11). The potential diplomatic, informational, military, and economic gains that could be realized through an EMP attack on the CONUS are innumerable. In fact, mitigating the potential effects of EMP on the U.S. grid is a White House priority with strategy currently under development.[19] Meanwhile, Congress has pursued a strategy that addresses EMP and GMD via the EMP Commission, the Secure High-voltage

[16] 2008 EMP Commission, http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf (last visited Aug. 8, 2015).
[17] A. B. Pittock et al., 1 Direct Effects of Nuclear Detonations (John Wiley & Sons Ltd 1986) [hereafter Direct Effects], http://dge.stanford.edu/SCOPE/SCOPE_28_1/SCOPE_28-1_1.1_Chapter1_1-23.pdf (last visited Aug. 8, 2015).
[18] 2008 EMP Commission, http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf (last visited Aug. 8, 2015).
[19] John Ostrich, Briefing: DOE/OE GMD Space Weather Program (Office of Electricity Delivery and Energy Reliability. 2015). Provided to authors.

Infrastructure for Electricity from Lethal Damage (SHIELD) Act;[20] Grid Reliability and Infrastructure Defense (GRID) Act;[21] and the Critical Infrastructure Protection Act (CIPA).

EMP is not the only phenomena with the ability to adversely impact modern society. In 2012, NASA reported a CME event believed to have been the most powerful near-Earth miss in more than 150 years. According to one expert, "If it [CME] had hit, we would still be picking up the pieces."[22] Space weather events such as the 2012 super storm pose a severe risk to all electricity-powered technologies.[23]

While space weather, like EMP, has only recently become a national security focus, it has long impacted technology. In a warning to power industry leaders about the dangers of dismissing space weather, Murtagh explained, "We talk about our reliance on our advanced technologies today, but in 1921, they talked about their reliance on technologies in that day and [even then] space weather impacted the technologies."[24] The 1921 geomagnetic storm set telegraph wires and equipment on fire in telegraph offices. More recently, a geomagnetic storm in March of 1989 "caused major damage to electrical power equipment in Canada, Scandinavia, and the United States." [25]

In 2008, the Congressional Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack (2008 EMP Commission) found: "Should significant parts of the electrical power infrastructure be lost for any substantial period of time, the Commission

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[20] Secure High-voltage Infrastructure for Electricity from Lethal Damage Act, S. H.R. 2417, 113th Cong. (2013-2014).
[21] Grid Reliability and Infrastructure Defense Act, S.H.R.4298, 113th Cong. (2013-2014).
[22] Dr. Tony Phillips, Near Miss: The Solar Superstorm of July 2012 (Nat'l Aeronautics & Space Admin. 2014) [hereafter 2012 near Miss], http://science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm/ (last visited Aug. 8, 2015).
[23] Severe Space Weather Events—Understanding Societal and Economic Impacts (The Nat'l Academies Press 2008) [hereafter Severe Space Weather Report], http://www.nap.edu/openbook.php?record_id=12507 (last visited Aug. 8, 2015).
[24] Ibid.
[25] Charles E. Rossi, Information Notice No. 90-42: Failure of Electrical Power Equipment Due to Solar Magnetic Disturbances (NUCLEAR REGULATORY Comm'n OFFICE OF NUCLEAR REACTOR REGULATION 1990) [hereafter NRC Information Notice], http://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/1990/in90042.html.

believes that the consequences are likely to be catastrophic … *many people may ultimately die for lack of the basic elements necessary to sustain life in dense urban and suburban communities*."[26] The same year, the National Academy of Sciences (NAS) released a similar report with independent but comparable findings: Although the probability of "…blackout resulting from an extreme space weather event is low; the consequences of such an event could be very high, as its effects would cascade through other, dependent systems."[27] The report asserted that "collateral effects of a longer-term outage would likely include, for example, disruption of the transportation, communication, banking, and finance systems, and government services; the breakdown of the distribution of potable water owing to pump failure; and the loss of perishable foods and medications because of lack of refrigeration.[28]

Where space weather is concerned risk industry assessments are in perfect alignment with the previous studies. Lloyds, the world's leading insurance syndicate, notes: "As the North American electric infrastructure ages and we become more and more dependent on electricity, the risk of a catastrophic outage increases ... Because of the potential for long-term, widespread power outage, the hazard posed by geomagnetic storms is one of the most significant."[29] The assessment further states, "While the probability of an extreme storm occurring is relatively low at any given time, <u>it is almost inevitable that one will occur eventually</u>."[30] Lloyds estimated, in

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[26] 2012 near Miss, http://science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm/ (last visited Aug. 8, 2015).
[27] Severe Space Weather Report, http://www.nap.edu/openbook.php?record_id=12507 (last visited Aug. 8, 2015).
[28] Ibid.
[29] Trevor Maynard, Neil Smith & Sandra Gonzalez, Solar Storm Risk to the North American Electric Grid (Lloyds 2013) [hereafter Lloyds], HTTPS://WWW.LLOYDS.COM/~/MEDIA/LLOYDS/REPORTS/EMERGING%20RISK%20REPORTS/SOLAR%20STORM%20RISK%20TO%20THE%20NORTH%20AMERICAN%20ELECTRIC%20GRID.PDF (last visited Aug. 8, 2015). (*Authors' Note*: A Carrington-level, extreme geomagnetic storm is almost inevitable in the future. While the probability of an extreme storm occurring is relatively low at any given time, it is almost inevitable that one will occur eventually. Historical auroral records suggest a return period of 50 years for Quebec-level storms and 150 years for very extreme storms, such as the Carrington Event that occurred 154 years ago. The risk of intense geomagnetic storms is elevated as we approach the peak of the current solar cycle. Solar activity follows an 11-year cycle, with the most intense events occurring near the cycle peak. For the current Cycle 24, the geomagnetic storm risk [wa]s projected to peak in early 2015; [however, significant risk remains]. As the North American electric infrastructure ages and we become more and more dependent on electricity, the risk of a catastrophic outage increases with each peak of the solar cycle. Because of the potential for long-term, widespread power outage, the hazard posed by geomagnetic storms is one of the most significant.).
[30] Ibid.

some cases, collateral damages would exceed a trillion dollars.[31] Lloyds also predicts the failure of backup generators (EDGs) at hospitals, which this study examines in depth due to nuclear station reliance.

In addition to historic information and prediction modeling, recent component testing from the Idaho National Laboratory (INL) demonstrated that mitigation of primary E3 waves propagated by space weather are particularly problematic. Scott McBride, a program manager with INL, explains,

> [A] HEMP filter … is installed at locations like data centers, call centers, critical DOD mission facilities, hospitals, potentially, and other critical loads; it's designed to protect against E1 and E2 components of a HEMP pulse. E3 is the "low and slow" component of the EMP pulse, which is what is significant with geomagnetic disturbance and potential effects on the power grid ... With that HEMP filter in the circuit and with that circuit bi-

[31] Andrew Simpson, Lloyds of London Report on Cyber Attack on U.S. Power Grid (Looyd's of London 2015) [hereafter Lloyds Cyber Report], http://www.scribd.com/doc/270914376/Business-Blackout-Looyd-s-of-London-report-on-Cyber-Attack-on-U-S-Power-Grid. (Last visited Aug. 8, 2015). (*Authors' Note:* the hackers spend months researching the U.S. electricity markets, control systems and networks. They identify critical information flows, networks, devices and companies, and eventually begin writing a piece of malware designed to spread through generator control rooms without alerting system security teams. The attack triggers a widespread blackout plunging 15 states and Washington DC into darkness and leaving 93 million people without power. It shuts down factories and commercial activity responsible for 32 percent of the country's economic production. Companies, hospitals and public facilities with backup generators are able to continue operations, but all other activities requiring power are shut down. This includes phone systems, Internet, television and radio, streetlights, traffic signals, and many other facilities. Images of a dark New York City make front pages worldwide, accompanied by photographs of citizens stuck underground for hours on stranded subway cars and in elevators in the summer heat. Although only a few people are hurt in the initial incident, the long power outage does take its toll in human deaths and injury. There are many accidents resulting from the blackout, including road traffic and industrial accidents. There are people hurt in riots, looting and arson attacks. As the power cuts continue through the hot summer months, heat stress affects older and infirm people, with a rash of deaths reported in nursing homes. Backup generator failures in hospitals result in treatment equipment failing. People are reported sick from eating food that has defrosted or not been properly cooked. In some cases industrial accidents cause environmental damage, and water treatment failures result in pollution to water courses. Evidence from historical outages and indicative modeling suggests that power interruptions already cost the U.S. economy roughly $96Bn annually. However, uncertainty and sensitivity analysis suggest this figure may range from $36Bn to $156Bn. Currently more than 95 percent of outage costs are borne by the commercial and industrial sectors due to the high dependence on electricity as an input factor of production. The majority of these costs (67 percent) are from short interruptions lasting five minutes or less. This estimate only provides the expected annual economic loss in an average year, and does not give an indication for the losses that might occur due to a single extreme event. Economic impacts include direct damage to assets and infrastructure, decline in sales revenue to electricity supply companies, loss of sales revenue to business and disruption to the supply chain. The total impact to the U.S. economy is estimated at $243Bn, rising to more than $1T in the most extreme version of the scenario.)

> passed, a key take away we found when we do these injection tests – the harmonics we measured inside the load trailer were about 50% higher with the EMP filter in the circuit than without that filter in the circuit … What we have is a filter designed to protect against one challenge that exacerbates the problems due to geomagnetic disturbances. [32]

In light of historic information, prediction models, and component testing, it is assumed that EMP and GMD will at some point adversely impact all aspects of technology and society if not mitigated. With this understanding, we will examine these phenomena as they relate to nuclear power plants, reactor systems, and operations.

Risks to Nuclear Power Stations

The Design Basis Illusion

Over the last few decades, the U.S. grid and technologies that use it to function have become co-dependent. As a result, present *design basis* requirements (risk mitigation features required for individual power stations to receive operations certification) from NRC do not address EMP or GMD as a risk to nuclear power stations because stations are assumed to have constant access to a reliable power grid. Design basis studies, however, only examine and mitigate obvious region specific threats that could impact a facility such as flooding, hurricanes, earthquakes, fires, and to a limited degree, security concerns. In addition, threats are treated as isolated and independent events. In other words, it is assumed they will not occur simultaneously or result in compound collateral effects involving more than one facility, function, or component.

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[32] Scott McBride, GMD Impacts to Power Grid Infrastructure: Scott McBride, Idaho National Laboratory [hereafter Scott McBride presentation], https://www.youtube.com/watch?v=eex9utoc5du. (Last visited Aug. 8, 2015). ([*Authors' Note:* This lecture was the first release of the DOD study findings on the actual effects of an EMP an operational power grid. This text transcribed from lecture footage.]: "This [slide] shows the inside of the load trailer … on the left hand side we have a HEMP filter … that filter is installed at locations like data centers, call centers, critical DOD mission facilities, hospitals, potentially, and other critical loads. It's designed to protect against E1 and E2 components of a HEMP pulse … we know how to protect against … E1 and E2. E3 is the low and slow component of the EMP pulse, which is what is significant with Geomagnetic Disturbance and potential effects on the power grid ... With that HEMP filter in the circuit and with that circuit bi-passed, a key take away we found when we do these injection tests the harmonics we measured inside the load trailer were about 50 percent higher with the EMP filter in the circuit than without that filter in the circuit. So now we've got what we have is a filter designed to protect against one challenge that exacerbates the problems due to geomagnetic disturbances.).

As a consequence of design-basis logic, no nuclear power station (currently under license) is required to endure the effects of EMP, GMD, or a substantial interruption of the power grid (longer than 7 days) or long-term "station blackout." Furthermore, most back-up power systems are "not intended for beyond design basis events."[33] David Lochbaum, former Reactor Technician Instructor with the NRC and Director at the Union of Concerned Scientists' Nuclear Safety Project, notes, "The problems that led to the disaster at Fukushima Daiichi exist wherever reactors operate."[34] Fukushima is a case study in the failed logic of design basis facility preparation and it transpired in a modern nation that modeled its technological and nuclear regulatory scheme after the United States.[35]

The assurances in this context also refer to defense-in-depth, a plant safety approach that has been in use at the NRC for decades. It can be thought of as overlapping layers of protection used to safeguard against certain types of hazards tailored to the design of each facility. While this approach is the industry standard, both the Fukushima and TMI disasters demonstrate layers can and do fail simultaneously. These compound failures are called *common-mode failures*. The NRC and industry continue operating on the premise that common-mode failures are "extremely remote" or "unlikely."

Lochbaum believes that if an EMP affected an automated process or instrumentation within a plant control room, it would be difficult for workers to accurately gauge and respond to events inside the reactor.[36] Lochbaum also stated that although technicians practice drills in which SCADA-based devices such as automated controls and instrument panels malfunction or go offline, they do not usually do so with all automated processes suspended, nor are they encouraged to do so: "Few exercises are performed with all of the control systems unavailable.

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[33] Regulatory Guide 1.9 Application and Testing of Safety-related Diesel Generators in Nuclear Power Plants(4th ed. Nuclear Regulatory Comm'n 2007) [hereafter Regulatory Guide 1.9], http://www.nrc.gov/reading-rm/doc-collections/reg-guides/power-reactors/rg/01-009/01-009.pdf (last visited Aug. 8, 2015).
[34] David Lochbaum et al., 978-1-59558-908-8, Fukushima: The Story of a Nuclear Disaster at vii-viii (1st ed. The New Press 2014) [hereafter FUKUSHIMA].
[35] Fukushima, p.112. (*Authors' Note*: "Fukushima wasn't an accident in a backwater country; it was occurring in a highly educated, science-savvy Japan, using technology and a regulatory playbook borrowed largely from the Americans. Thirty-one aging carbon copies of the reactors at Fukushima Daiichi were operating around the United States.")
[36] David Lochbaum (Personal communication), Jun. 29, 2015.

After Fukushima, some crews while in training attempted to duplicate the widespread loss that the operators in Japan faced. The initiative was quickly squelched on grounds that it distracted operators from required training."[37] Further, Lochbaum claims that to his knowledge there has "never" been a large-scale drill or training exercise in which more than one plant simulated complete power loss.[38]

Given the concerns Lochbaum raises, further inquest was made as to the survivability of our nation's nuclear power plants if logistical components such as cell phones, transportation infrastructure, and electrical power were significantly degraded by an EMP event in keeping with the large-scale, long-term power outage outlined in the 2008 EMP Commission Report. Lochbaum's answer echoes the very purpose of this paper: "I have never evaluated this scenario nor read anyone else's evaluation of this scenario."[39] In other words, according to an industry expert, it is unlikely anyone has a clear view on how our current procedures would function in the wake of an EMP or GMD induced mass power failure.

Lochbaum's inputs raise considerable concerns about current mitigation strategies, the reliance on automated systems within nuclear power plants, and the degree to which the NRC and nuclear power as an industry are ready or able to handle potential widespread and diverse threats posed by EMP and GMD events. In order to address a potential crisis, it is important to understand what scenarios we currently plan for -- chiefly "design basis" failures. All of this leads us to ask: what is the NRC and industry ultimately trying to prevent? The answer is: meltdown.

What is Meltdown?

At a nuclear power station, fission is used to generate electricity in a reactor. Heat within a reactor is harnessed by storing fuel rods and control rods in a vessel(s) containing water. When heated, water within the containment vessel evaporates into steam, which then passes over a turbine. Turbine movement converts mechanical energy into electricity, which is in turn captured and sent off station to the grid.

[37] David Lochbaum (Personal communication), Jun. 29, 2015.
[38] Ibid.
[39] David Lochbaum (Personal communication), Jun. 29, 2015.

Once Fukushima's reactors were tripped offline after the 2011 Japanese earthquake -- something they were designed to do in a quake -- most of the challenges in that complex scenario remained and ultimately overwhelmed operators. Nearly all nuclear power stations, regardless of age, require off station or Direct Current (DC) battery power (as a backup) to continue the core's vital cooling functions. "Power is required since the fuel rods and chain reaction within a reactor continues [sic] to generate heat even once a reactor is tripped. When the reactor is shutdown, the core will still continue to generate decay heat. The heat is removed by bypassing the turbine and dumping the steam directly to the condenser."[40]

In an emergency, a reactor may continue to heat steam within the system until the containment vessel material (usually steel or concrete) can no longer contain internal pressures. The consequent release and venting of radioactive steam is called a plume. Plumes can travel thousands of miles. After Fukushima, radiation levels on West Coast of the U.S. rose to within .5 rem (a unit of radiation dosage) from thresholds requiring a national response and the administration of potassium iodide to segments of the U.S. population.[41] U.S. nuclear plants are only required to provide enough iodide to treat exposed persons within a ten-mile plume ring should a facility vent or lose containment. Fukushima was more than 5,400 miles away from the U.S. coast.

Once fuel rods undergo further heating within the core due to loss of coolant or circulation, these rods may melt and release even higher-levels of radiation into a new or active plume. This typically occurs around 800-900 degrees Celsius when the zirconium alloy cladding that is used to encase nuclear fuel rods become molten and ignite.[42] This chemical reaction is referred to as meltdown.

To prevent meltdown, boiling water reactors may use "rod and fuel removal" (a very slow process), injections of boron gas (which slows the chain reaction), or circulation of cool water to regulate temperatures. All processes rely on electricity -- removal of fuel and control rods from

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[40] Boiling Water Reactor (BWR) Systems USNRC Technical Training Ctr. [hereafter BWR Systems], http://www.nrc.gov/reading-rm/basic-ref/teachers/03.pdf (last visited Aug. 8, 2015).
[41] Fukushima, p. 139.
[42] Fukushima, p.7.

the core requires hydraulic pumps, pulleys, and mechanical push-pull rods; release of boron is controlled via sensors, pumps, and valves; and finally, the use of cool water requires valve switching and pumps. Under some conditions, pumps themselves may fail due to electromagnetic interference. For example, testing in the realm of cyber technology has shown that altering SCADA programming can lead to the physical destruction of the devices they govern. In similar tests, the 2008 EMP Commission found EMP can cause SCADA systems to behave in a manner different than their original programming which could lead to device failure or similar destructive sequences. In Fukushima's case, all reactors tripped offline due to the quake. After the trip, power from another source was required to continue powering functions needed to prevent overheating and meltdown.

Once the fuel rods melt and fall to the floor of the reactor containment building, it may initiate another chemical reaction and generate even more pressure and poisonous gases as it contacts the stone floor. After reaching critical pressures, radioactive laden gas may be intentionally or unintentionally released as a plume and contaminate the environment. In addition to a requirement to cool the core, pools housing fuel rods (submerged in water) generate heat for months after the rods are removed from the core. Like a reactor, heat sinks require a constant supply of water to remove heat. Without water evaporation and steam will build to critical pressures, and similar to reactors, rupture their housing.

In the wake of Fukushima, the NRC formed the Near-Term Task Force to assess whether or not such an event could happen in the U.S.. The NTTF concluded it could not be ruled out, the nuclear industry braced for what it believed would be an inevitable uptick in NRC and public pressure that would ultimately require costly upgrades for beyond design basis events.[43] In 2013,

[43] STATION BLACKOUT MITIGATION STRATEGIES (NUCLEAR REGULATORY COMM'N 2013) [HEREAFTER MITIGATION STRATEGIES], HTTP://PBADUPWS.NRC.GOV/DOCS/ML1317/ML13171A061.PDF (LAST VISITED AUG. 8, 2015). (*Authors' Note:* "The Nuclear Regulatory Commission (NRC), in the staff requirements memorandum (SRM) on SECY-11-0124, dated October 18, 2011, approved the NRC staff's proposed actions to implement without delay the development of a regulatory basis, proposed rule, and implementing guidance to enhance the capability of nuclear power plants to maintain safety through a prolonged station blackout (SBO) (Ref. 1). The anticipated regulatory actions originate in large measure from Recommendations 4 and 7 of *The Near-Term Task Force Review of Insights from the Fukushima Daiichi Accident* (NTTF report), Enclosure (1) to SECY-11-0093, *The Near-Term Report and Recommendations for Agency Actions Following the Events in Japan*, dated July 12, 2011 (Ref. 2). In SRM-SECY-2011-0124, the Commission directed the NRC staff to: initiate a rulemaking for

the NRC, initially receptive to the NTTF's recommendations, opened a public comment period on the idea of placing stricter safety rules on operators.[44] In 2011, the NRC received several requests from nuclear experts including Tomas Poptik's petition (PRM 50-96) to provision long-term back-up power to protect nuclear stations and spent fuel sites from station blackouts.[45]

To inoculate itself from impending criticism and tighter safety regulations, the industry developed and self-imposed a beyond-design basis disaster mitigation plan called FLEX (diverse and flexible mitigation capacity). "FLEX envisioned a rapid deployment force of portable equipment such as back-up pumps, generators, batteries, and chargers that would be pre-staged at or near nuclear facilities."[46] According to Lochbaum, "The industry has always believed that the best defense is a good offense."[47] In addition to choosing its own medicine, the implementation of FLEX allowed industry to stave off potentially costly upgrades and infrastructure improvements arising of new regulations.

Unfortunately, one of the key lessons from Fukushima was the impact a local or regional disaster can have on logistics. Logistics is the backbone of the FLEX program which relies on deployments from two centralized U.S. locations. Fukushima proved optimistic dependence on an uninterrupted supply chain during contingencies could be disastrous. In just a matter of hours after the tsunami and earthquake, the plant remained disconnected from a devastated power grid.

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recommendation 4.1, *Station Blackout Regulatory Actions*, as an advance notice of proposed rulemaking (ANPR); designate the SBO rulemaking associated with Near-Term Task Force (NTTF) Recommendation 4.1 as a high priority rulemaking; craft recommendations that continue to realize the strengths of a performance-based system as a guiding principle and consider approaches that are flexible and able to accommodate a diverse range of circumstances and conditions).

[44] Station Blackout: A Proposed Rule By the Nuclear Regulatory Commission on 03/20/2012(United States Nat'l Archives & Records Admin. 2012) [hereafter Station Blackout], https://www.federalregister.gov/articles/2012/03/20/2012-6665/station-blackout (last visited Aug. 8, 2015). (*Authors' Note*: the U.S. Nuclear Regulatory Commission (NRC or the Commission) is issuing this Advance Notice of Proposed Rulemaking (ANPR) to begin the process of considering amendments of its regulations that address a condition known as station blackout (SBO). SBO involves the loss of all onsite and offsite alternating current (ac) power at a nuclear power plant. The NRC seeks public comment on specific questions and issues with respect to possible revisions to the NRCs requirements for addressing SBO conditions to develop new SBO requirements and a supporting regulatory basis. This regulatory action is one of the near-term actions based on lessons-learned stemming from the March 2011 Fukushima Dai-ichi accident in Japan.).

[45] Mitigation of Beyond-Design-Basis Events (NRC 2015) [hereinafter NRC-2011-0189], http://www.regulations.gov/#!documentDetail;D=NRC-2011-0189-0040.

[46] Fukushima, p.173.

[47] Ibid.

Diesel generators that could normally provide backup electricity to cooling pumps were inundated with water while others could not be connected due to electrical distribution system damage. With no off station power, the back-up batteries provided interim cooling functions, but after battery depletion, Fukushima experienced a full-scale sustained station blackout.

The interruption of essential logistics is not unique to Fukushima. After Hurricanes Katrina and Rita fuel delivery impacts were widespread as pipelines and refineries shut down due to the evacuation of workers, flooding, and power outages. Almost eight percent of the nation's oil and gas production was halted leading to long lines at filling stations, with many running out of gas.[48, 49] Such scenarios should be anticipated during any large scale disaster including EMP or GMD. While the NRC and industry make no provision for such eventualities, both DHS and FEMA disaster planning documents dealing with nuclear and radiological disasters anticipate widespread disruptions that will impede timely recovery.[50] The nuclear industry remains convinced present regulations and safety protocols are adequate. Consequently, requirements across Japan, whose regulatory system was modeled after the NRC's, as well as power stations

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[48] Lawrence Kumins & Robert Bamberger, Oil and Gas Disruption from Hurricanes Katrina and Rita (Cong. Research Serv. 2005) [hereafter Oil and Gas Disruption], http://fpc.state.gov/documents/organization/55824.pdf (Last Visited AUG. 8, 2015). (*Authors' Note:* nearly 1.6 mbd of crude oil — the equivalent of 7.6% of U.S. oil consumption — was produced on the Gulf of Mexico Federal Offshore before the hurricanes struck. Production was virtually halted in the wake of both storms, as production facilities were evacuated and wells were shut down. The storms destroyed 111 production platforms, and 52 were seriously damaged. A number of drilling rigs were destroyed, which will limit future production from new wells yet to be completed.).

[49] Jad Mouawad & Simon Romero, *Gas Prices Surge As Supply Drops,* 2005 NY TIMES, Sept. 1, 2005 at (2005) http://www.nytimes.com/2005/09/01/business/gas-prices-surge-as-supply-drops.html?_r=0. (*Authors' Note:* for the first time since the 1970s, gasoline lines reappeared yesterday in some corners of the country. Three days after Hurricane Katrina dealt a devastating blow to the nation's largest energy hub, the worst-case possibility was quickly becoming a reality: gasoline prices surging well above $3 a gallon, with some consumers complaining of price gouging; service stations in a handful of locations running out of gas; drivers rushing to fill their tanks, only to find themselves waiting in line with others.).

[50] Catastrophic Incident Annex (Fed. Emergency Mgmt. Agency 2008), http://www.fema.gov/pdf/emergency/nrf/nrf_CatastrophicIncidentAnnex.pdf. (*Authors' Note:* the nature and scope of the catastrophic incident will include major natural or manmade hazards including chemical, biological, radiological, nuclear, or high-yield explosive attacks, and cyber-attacks. A catastrophic incident has unique dimensions/characteristics requiring that response plans/strategies be flexible enough to effectively address emerging needs and requirements. A catastrophic incident will occur with little or no warning. Some incidents may be well underway before detection. Multiple incidents will occur simultaneously or sequentially in contiguous and/or noncontiguous areas. Some incidents, such as a biological WMD attack, may be dispersed over a large geographic area and lack a defined incident site. A catastrophic incident will produce environmental impacts that severely challenge the ability and capacity of governments and communities to achieve a timely recovery. Federal resources must be capable of mobilization and deployment before they are requested via normal NRF protocols.).

across the U.S. require backup batteries to supply station power for only eight hours after off-station power loss.

After the earthquake, with no communications, no power, and no ability to get supplies to the plant due to choked roads and debris, TEPCO employees, frantic to restore power, resorted to rummaging through piles of rubble and mud to find car batteries they could use to power water pumps. "Protective clothing also became scarce. Meals consisted of biscuits and dried food, and water was rationed."[51] In addition, the dangers of the disaster were compounded by an inability to deliver fresh crews to the site, forcing beleaguered crews to work eight days straight with little or no sleep. At Fukushima, the unthinkable happened and it shattered the design-basis illusion. It was a desperate situation that no one was trained to cope with. With power gone, there was no way to know what was happening inside the reactors.[52]

Fukushima, like any major transportation disaster investigated by the NTSB, can provide regulators and the industry operators with critical takeaways useful in the prevention of future accidents. However, in spite of the years since Fukushima, the NRC and industry is on track to maintain status quo. Presently, the NRC's updated station blackout mitigation regulation is stalled and industry remains keen on FLEX - a program it believes will assuage concerns about beyond design basis threats. *However, alleviating a concern and implementing needed design remedies are not the same.* FLEX has the capacity to be quickly outstripped or proven to be untenable due to logistical complications. While situations such as Fukushima are possible at any U.S. nuclear facility, one type of common-mode failure stands apart in its ability to produce a cascade of failures at one to nearly all stations simultaneously – EMP and GMD.

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[51] Ibid, p.86.
[52] Ibid.

EMP and GMD

Although it poses no direct threat to the human body, EMP will severely damage electronic components to include most computer electronics, circuit boards, SCADA systems, and critical components of the electric grid such as Large Power Transformers (LPTs).[53]

Exposure levels from EMP can vary widely from as low as 5-10 kilovolts/per meter squared (kV/m) to 50 kV/m depending on the distance and exposure to the EMP source. During Congressional testimony July 16, 1997, Dr. Lowell Wood (a physicist and 30-year expert on EMP) and Dr. George Ullrich (at the time, Deputy Director of the Defense Special Weapons Agency) testified that a "megaton class weapon … detonated 400 kilometers (~250-300 mi) above Omaha [Nebraska] … [would cover] the entire contiguous 48 States … from Boston to Los Angeles, from Chicago to New Orleans."[54] Further, Dr. Wood noted with conventional nuclear weapons that a "one megaton class would impose field strengths of at least 10 kV/m all over the continental United States. The actual field strengths would be more in the neighborhood of 20,000 to 50,000 volts per meter [(20-50 kV/m)]".[55] Dr. Wood would later serve on the EMP Commission, whose preliminary findings, 10 years after his 1997 testimony, remained consistent.

An additional concern with a nuclear or manufactured EMP is the pulse consists of three distinct energy waves. Each wave has uniquely destructive effects on electrical components. The E1 wave occurs within one billionth of a second upon nuclear detonation and is capable of disabling surge protectors.[56] The E2 phase can cause significant structural damage to circuitry and electrical components, while the E3 phase (which lasts around 90-120 seconds after the initial E1 pulse and couples large currents to long electrical and communications lines) poses the greatest significant threat to LPTs. E3 can overload LPTs and may cause structural damage (Figure 6).

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[53] Threat Posed by Electromagnetic Pulse (EMP) to U.S. Military Systems and Civil Infrastructure (Fed'n of Am. Scientists 1998) [hereafter 1998 EMP Congressional Hearings], http://fas.org/spp/starwars/congress/1997_h/has197010_1.htm.; 2008 EMP Commission. http://www.empcomission.org/docs/A2473-EMP Commission-7MB.pdf.

[54] 1998 EMP Congressional Hearings. http://fas.org/spp/starwars/congress/1997_h/has197010_1.htm

[55] Ibid.

[56] 2008 EMP Commission. http://www.empcomission.org/docs/A2473-EMP Commission-7MB.pdf

The damaging effects of HEMP cannot be overstated. Based on EMP Commission testing and Dr. Wood's Congressional testimony, it should be understood that most, if not all, SCADA and LPTs will likely suffer structural damage, malfunction or failure if affected by EMP.[57]

A geomagnetic event has the potential for even wider effects than manufactured EMP. According to the National Research Council, during a space weather event, charged particles "as much as 10^{16} grams or more of coronal material" can erupt from the sun and are sent at speeds of up to "3000 kilometers/second" from the sun in a linear line.[58] If the CME trajectory is such that the CME cloud directly influences the Earth, a geomagnetic storm becomes likely. Charged particles from the CME interact with the geomagnetic field of Earth, racing down geomagnetic field lines generating a similar atmospheric energy pulse to that of EMP-E3. Although it lacks the E1 and E2 phase, a solar storm's E3 phase is much larger and is capable of encompassing the majority of the CONUS.[59] In order for a CME to be "maximally geoeffective" and create a magnetic storm, a CME must "(1) be launched from near the center of the Sun onto a trajectory that will cause it to impact Earth's magnetic field; (2) be fast (≥ 1000 kilometers/second) and massive, thus possessing high amounts of kinetic energy; and (3) have a strong magnetic field whose orientation is opposite that of Earth's."[60] According to John Ostrich, head of Infrastructure Security and Energy Restoration Office of Electricity Delivery and Energy Reliability at the DOE, "E3 from GMD is more dangerous than E3 resulting from EMP as it lasts longer."[61] In other words, the E3 pulse from GMD has more time to build resulting in greater damage to the grid.

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[57] 1998 EMP Congressional Hearings. http://fas.org/spp/starwars/congress/1997_h/has197010_1.htm
[58] Severe Space Weather Report, http://www.nap.edu/openbook.php?record_id=12507 (last visited Aug. 8, 2015).
[59] Electromagnetic Pulse: Effects on the U.S. Power Grid 1-6 (FERC 2010) (by simulating the effects of a 1 in 100 year geomagnetic storm centered over southern Canada, the computer models estimated the sections of the power grid expected to collapse during a major EMP event. This simulation predicts that over 300 EHV transformers would be at-risk for failure or permanent damage from the event. With a loss of this many transformers, the power system would not remain intact, leading to probable power system collapse in the Northeast, Mid-Atlantic and Pacific Northwest, affecting a population in excess of 130 million (Figure 1). Further simulation demonstrates that a storm centered over the northern region of the United States could result in extending the blackout through Southern California, Florida and parts of Texas.), http://www.ferc.gov/industries/electric/indus-act/reliability/cybersecurity/ferc_executive_summary.pdf (last visited Nov. 30, 2015).
[60] Ibid.
[61] John Ostrich (Personal communication), Jul. 28, 2015.

When factors align, GMDs have the energy to create geomagnetic currents in the form of Ground Induced Currents (GICs), which like E-3, may devastate electronics and equipment necessary for the generation, transmission, and distribution of electricity. Figure 14 is a snapshot of historic data detailing strengths of CME-induced geomagnetic storms in terms of nano-Teslas (nT) and the Starfish Prime experiments in kilovolts per meter (kV/m). The table provides a snapshot of the relative energy both CME-created GMD and manufactured EMP events may emit. These comparisons are important as the following sections discuss the impact of these fields and subsequent electrical disruption of components considered essential to safe nuclear reactor operations.

SCADA Systems

SCADA systems regulate the large majority of minute-to-minute data functions and controls within all components of the electric grid and plants. These functions include real-time measuring, reading and adjustment of voltages, currents, reactance, line status (breakers, switches, re-closers, cap breaks, voltage regulations) and transformer status as well as identifying outages and even providing means to adjust load distributions and substation maintenance.[62] The importance of information both to mitigate and cope with a nuclear crisis cannot be over stated. Most of this critical information is provided by SCADA.

The interconnectedness between a power plant and the average home is significant. At all levels of the relationship (Figure 2) SCADA devices are present. Within a nuclear plant, key functions such as pump regulation, turbine speeds, temperature control, temperature and pressure monitoring; electrical output and other aforementioned vital functions become difficult if not impossible to accurately measure. Should SCADA go offline (Figure 3 for an example of a Master SCADA Control System in Canada's Darlington nuclear power plant) it presents a serious risk to the plant and collateral areas. The EMP Commission noted:

> Modern power plants all utilize complex protection and control systems to maximize efficiency and provide safety. They all have common electrical characteristics in order

[62] SCADA Systems - Utility 101 Session with Rusty Williams (AFLGlobal via YouTube 2012) [hereafter SCADA Systems], https://www.youtube.com/watch?v=vv2CoTiaWPI (last visited Aug. 8, 2015).

for them to be useable by all the various purposes to which electricity is put. Electronics have largely replaced all the electromechanical devices in older plants and are used exclusively in plants of the past one or two decades. Even generator exciters now have microprocessors and analog-to-digital converters. These electronics and, thus, the power plant itself are highly vulnerable to EMP assault. Identifying and locating damaged generation plant equipment with electronic sensors and communication interdicted and/or unreliable due to EMP and repairing the system would be a complex and time-consuming process, even when personnel and parts are readily available.[63]

While the EMP Commission examined and subsequently classified some of its findings on the effects of EMP on fossil fuel-based power stations and components, the Commission report characterizes the likely effects of EMP on nuclear stations as: "the key difference with nuclear power plants is [sic] the extensive manual control capability and training, making them less vulnerable."[64] In addition, the Commission noted nuclear plants are not as likely to be impacted by an E1 pulse due to the "nature of their protection schemes."[65] The EMP Commission assessment does not say that nuclear power plants are invulnerable to EMP, or that an EMP would not have catastrophic consequences on nuclear power plants, but observes --relative to most other kinds of power plants--nuclear power plants are more secure. However, because the unclassified EMP Commission reports are written as executive summaries for policymakers and address a range of EMP vulnerabilities across all critical infrastructures, of necessity the reports could not treat in detail all of the catastrophic consequences of EMP (such as firestorms consuming cities because of electrical fires and gas line explosions; toxic clouds, fires, and chemical spills that would pose widespread risks and impede recovery due to the EMP vulnerability of various industries; or the mass destruction and collateral consequences resulting from the widespread crashing of airliners).

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[63] 2008 EMP Commission, http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf, p.35 (last visited Aug. 8, 2015).
[64] Ibid.
[65] 2008 EMP Commission, http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf, p. (last visited Aug. 8, 2015).

However, the EMP Commission clearly understood the potential catastrophic consequences of nuclear reactor vulnerability. Indeed, one of the most senior scientists on the EMP Commission staff, Dr. George Baker, was the chief critic of the Sandia Labs 1982 Christmas Study, faulting it for grossly underestimating the EMP threat to nuclear reactors.

Moreover, the EMP Commission Chairman, Dr. William Graham, even after the Commission terminated in 2008, continued to press the Nuclear Regulatory Commission to protect nuclear reactors from EMP. *Electric Armageddon*, a book published by the EMP Task Force on National and Homeland Security (a Congressional Advisory Board that succeeded the EMP Commission) describes the potential catastrophic consequences of nuclear reactor vulnerability, and continuing efforts by Dr. Graham and the Task Force to correct that vulnerability -- to no avail.

Precisely because the Nuclear Regulatory Commission has ignored warnings that failure to protect nuclear power reactors from EMP could have catastrophic consequences for the nation by the Congressional EMP Commission, the EMP Task Force, and others, this new study is all the more timely, urgent, and important. In fact, according to Dr. Peter Pry, a leading authority on EMP who served on the EMP Commission, "Of all the potential catastrophic consequences of an EMP, nuclear power reactor vulnerability is among the worst, and by itself constitutes an existential threat to society."[66]

Accordingly, this in depth study of the technical vulnerability of nuclear power reactors to natural and manmade EMP, and the consequences of that vulnerability, it is hoped may provide the necessary corrective before it is too late. The reader may be aware this study is written at a time when NASA estimates the likelihood of a geomagnetic super-storm is 12 percent per

[66] Peter Pry (Personal communication), Nov. 30, 2015.

decade, and the threat to society from nuclear proliferation and terrorism has never been greater.[67]

The NRC's continued use of the Christmas Study, as recently as October 21, 2015, to assuage concerns about risks to nuclear power stations warrants a close look at the Sandia report's claims.[68] Examination of the 1982 Christmas Study yielded more than a dozen key areas that make questionable its conclusion that EMP will not affect a nuclear power station's ability to safely perform cold shutdown.

The following factors were identified as shortfalls:

1. Solid-state components (circuit boards and computers) were not considered critical items required for shutdown. This is particularly problematic 30 years later as many essential plant functions have migrated to digital control schemata.
2. Off station power was considered an attenuation (dampening) mechanism rather than a component essential to preventing station blackout. While attenuation of E1 and E2 signals are important, E3 signals are carried and magnified by power lines. Moreover, off-station power is critical to reactor cold shutdown.
3. Potential damage from E3 waves were not adequately evaluated as the study dealt only with nuclear EMP. Without considering GMD, no study can conclude that "EMP" will not prevent safe shutdown as E1, E2, and E3 are part of the total threat phenomena.
4. Characteristics of a single plant were used to extrapolate findings to all others. However, each facility has unique properties due to individual designs and metrological composition.
5. Sole focus was on components and signal strengths inside the plant rather than both within and without.

[67] Jason Samenow, White House Releases Action Plan to Confront Real and Present Space Weather Threats (Washington Post 2015), https://www.washingtonpost.com/news/capital-weather-gang/wp/2015/10/29/white-house-releases-action-plan-to-confront-real-and-present-space-weather-threats/.
[68] Joint Meeting of the Federal Energy Regulatory Commission (FERC) and the Nuclear Regulatory Commission (NRC), 21 Oct, 2015. http://www.nrc.gov/reading-rm/doc-collections/commission/slides/2015/20151021/

6. Failure to perform a systems analysis to identify key nodes. The relationship between key components and their role in safe shutdown were not identified. For example, EDGs were assumed to function. If not, the power grid was assumed to be restored within eight hours. By the study's own admission, transformers would likely attenuate signals resulting in melting or fusing of internal windings. In some cases, this would necessitate replacement of transformers before station power could be brought back online. Such an effort would likely take days and depend heavily on logistics.
7. Estimates for signal failures induced on rotating equipment were not made. While many components were theoretically evaluated, many items essential to cooling such as pumps and condensers were excluded due to a lack of data. As noted previously, some testing indicates that such equipment will fail when SCADA are disrupted.
8. Used second-order approximation, "decent quality answer," or educated guesses were deemed sufficient.
9. Damage thresholds on equipment were not available due to lack of testing or because vendors considered data proprietary.
10. All measurements of EMP signals and assumed failures were theoretical or table-top assumptions. The study is, by its own admission, imprecise and cannot provide a level of statistical certainty.
11. It was assumed EDG's would function in spite of requiring at least four solid-state components and circuit boards to operate. If any of the following were affected, EDGs are likely to require repairs before they could provide power to a plant:
    a. Diesel Generator Load Sequencer
    b. Diesel Generator process control sensors
    c. Battery Charger
    d. AC Static Inverter
12. It was assumed station power would be restored in eight hours (the NRC's regulatory requirement).

13. Does not address electrical arcing. Arcing magnitudes may exceed carrier thresholds and discharge electricity in a manner analogous to energy release from a capacitor.[69]
14. Assumes common-mode failures are not possible. Such failures are possible as demonstrated at TMI in 1979, pre-dating the study, and again in 2011 at Fukushima. An inability to make proper control inputs, in both cases, resulted in radiological disasters.
15. Fails to address human factors. In the event of an EMP, which is a beyond design basis event, there is no training. Further, dynamics such as crew fatigue, exposure to radiation, and logistics within the plant were not explored at any level.

Research shortfalls such as those above demonstrate the 1982 Christmas Study's findings, methodologies, and underlying assumptions can be contested. And they were, both before and after the Christmas Report was released, experts inside and outside government hotly challenged many of the same shortfalls. A memo from Dr. G.H. Baker of the Defense Nuclear Agency (DNA) dated May 27, 1982, noted:

> We have not, as yet, investigated possible transient upset of electrical equipment … In addition, the present study has been limited to local plant effects, not with EMP effects on overall power grid (including MHD, ripple outages, etc.) … We cannot at this time completely rule out shutdown problems that may result from temporary upset of critical control equipment because EMP signals are in some cases expected to be comparable to normal operational signals. The statement on page 154 that 'no EMP protection is required for the plant,' is not supported by what we've done here [the study].[70]

Another scientist affiliated with Los Alamos National Laboratory (LANL) wrote Sandia's researchers,

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[69] Arc Flash Definition (DuPont 2012) [hereafter Arc Flash], http://www2.dupont.com/Electrical_Arc_Protection/en_GB/arc-flash/arc-flash-definition.html (last visited Aug. 8, 2015). (*Authors' Note:* an arc flash caused by an electric arc with 1,000 amperes or more can cause substantial damage, fire or injury. The massive energy released in the fault rapidly vaporizes the metal conductors involved, blasting molten metal and expanding plasma outward with extreme force. A typical arc flash incident can be inconsequential but could conceivably easily produce a more severe explosion. The result of the violent event can cause destruction of equipment involved, fire, and injury not only to the worker but also to nearby people. (Forces may exceed 100kPa (KiloPascal), and debris is spread up to 300meters/second with temperatures of up to 20,000°C).

[70] 1982 Christmas Report, http://prod.sandia.gov/techlib/access-control.cgi/1982/822738-2.pdf. p.301

> It is not the quality of these tests and analyses, for the most part, that I feel it necessary to challenge. Rather, it is the long chain of plausible but not provable assumptions that provide only a shaky foundation for the remaining fine-looking structure, and thus prevents the conclusions from having confidence levels anywhere near 99.5%. I think that with a sufficiently long chain of plausible assumptions one could reach almost any conclusion desired.[71]

The NRC also weighed in with reservations, "…the EMP signal may induce currents on existing plant control circuits that may cause several systems to behave in a manner for which they have not been programmed. The study should determine if this is possible and whether the possible consequences are acceptable or not."[72] In another memo from the NRC (dated April 28, 1982) the NRC notes:

> The study has not addressed systems upset, spurious or erroneous instrumentation signals, or computer print-out errors that might result from the EMP. Therefore, it is not clear that the chance of operator error, based on false instrument readings or induced process computer errors, in overriding automatic equipment operation would not be increased.[73]

This observation is interesting in light of the fact that at TMI erroneous readings and subsequent human errors contributed to a major radiation release.[74]

Condemnation was even brought to bear on rudimentary errors and omissions such as a failure to consider the effects of E3 waves, which often arrive later and have varied impacts not associated with E1 and E2. In a letter from Lawrence Livermore Laboratory (dated September 17, 1982) the research evaluator notes: "A more complete systems analysis of a nuclear power plant should be considered so that the vulnerability of the system, rather than individual components, is

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[71] Ibid. p.335.
[72] Ibid.
[73] Ibid.
[74] Backgrounder on the Three Mile Island Accident, Nuclear Regulatory Commission, 2014. http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

assessed."[75] In another memo from the DNA (dated December 10, 1982) the agency notes during meetings to review the study, "It's also not clear how man plays in the loop (if at all) such that human intervention could work around equipment malfunction."[76] DNA goes on to ask why communications lines were not evaluated and noted that the report's overall evaluation of a single facility should not be extrapolated to other nuclear power facilities with varied structures and topography.[77]

Finally, in no uncertain terms, the memo from NRC's instrumentation branch (dated September 9, 1982,) concluded:

> Signal upset effects not considered in this study can induce permanent damage by amplifying the effects of primary EMP induced disturbances (cascade effects). Hence, their exclusion leaves their study with very little meaning…[78]

In the wake of well-reasoned expert analysis, it is clear: the nuclear community was largely unwilling to embrace the study's findings at that time. It should be noted, EMP is not on the FEMA list of National Planning Scenarios[79] Consequently, no training plan exists for nuclear power plants. Thus, most are unlikely to practice EMP exercises at all.[80] No reports have ever contemplated the logistical issues created by an EMP event in regard to FLEX. Further, there is no mandate requiring workers to prove they can effectively mitigate meltdown events without the use of SCADA and off-site power.

EMP field test data on SCADA demonstrate systems are vulnerable to E1 pulse. According to EMP Commission testing SCADA fail every time they are exposed to EMP, exhibiting malfunctions that include port failures, control variance issues, failure to control the systems they

[75] 1982 Christmas Report, http://prod.sandia.gov/techlib/access-control.cgi/1982/822738-2.pdf. p.364.
[76] Ibid. p.336.
[77] Ibid. p.188, 364.
[78] Ibid. p.406.
[79] 2008 EMP Commission, http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf (last visited Aug. 8, 2015). p.60; National Preparedness Guidelines (United States Dep't of Homeland Sec. 2007), http://www.fema.gov/pdf/emergency/nrf/National_Preparedness_Guidelines.pdf (last visited Aug. 8, 2015).
[80] Ibid.

were designed to control, and even physical circuit damage such as burn out (Figure 4).[81] Even if an E1 pulse did not damage SCADA systems, lack of power from an E3 pulse, which can devastate transformers, disrupt the power grid and affect EDGs, can cause the same effect – the loss of accurate readings or even erroneous readings from SCADA devices.

During the Fukushima incident, a lack of information became a significant hindrance to crisis mitigation. As Lochbaum points out, "Under normal circumstances, reactor operators at Fukushima Daiichi had access to a wide range of information about the status of critical systems … but when the control rooms were disabled by the loss of electrical power, the steady flow of information had largely ceased."[82] Although a nuclear plant can technically operate without offsite power, it is unsafe to do so because any incident that requires safe shutdown becomes complicated. Losing SCADA or having SCADA behave illogically, as is possible according to the EMP Commission, could effectively compromise the integrity and safety of nuclear plants during and after an EMP or GMD event.

Siemens is a worldwide name in SCADA components. Ian Knowles, a SCADA account manager, stated that most SCADA devices such as PCLs and RTUs are only rated to 8 kV/m.[83] This implies a there is high likelihood of failure in the wake of an EMP burst, which will likely result in kV/m fields of at least 10 kV/m across the majority of the CONUS.

LPTs and Power Grids

As with SCADA systems, in order to understand the impact an EMP pulse could have on nuclear power facilities it is first necessary to understand the function of LPTs. These transformers are not like those on power lines in neighborhoods and commercial areas, but rather massive and complex systems (Figure 5), which take up to 18 months to create, test, ship, install, and cost up

[81] 2008 EMP Commission, http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf (last visited Aug. 8, 2015).
[82] Fukushima, vii-viii.
[83] Ian Knowles, Account Manager at Siemens, (Interview 23 July 2015) [hereafter Knowles Interview]. (Authors' Notes: Ian spoke to ALPF as a professional sales person in SCADA systems and not on behalf of Siemens. Within our conversation, Ian indicated that all SCADA devices he has encountered are rated for no higher than 8 kV/m fields. This would strongly indicate that any fields higher than 8 kV/m put all unprotected SCADA systems at risk of burnout or failure.

to 7.5 million USD each to construct.[84] Like SCADA systems, the electrical grid does not function without LPTs. LPTs are responsible for ramping up voltage at power plants, sending electricity over hundreds of miles of high-voltage wire, and bringing down voltage at substations in order to provide power to homes and businesses.[85]

LPTs are highly vulnerable to EMP and GMD pulses. In the case of HEMP, damage to LPTs, particularly the extra-high voltage (EHV) transformers, could occur because of either the E1, E2 or E3 waves. Even with relay protection, it is still evident based on historical events that the E3 phase (which occurs in both EMP and GMD events) can cause significant physical damage to LPTs. During the 1989 Quebec blackout for instance, at least two transformers and more than 46 other pieces of electrical equipment, ranging from oscillographs to capacitors, were reported as damaged from the GIC that occur during GMD activity and associated E3 pulses.[86] (Figure 5 illustrates the physical damage that can occur because of both EMP and GMD events).

In fact, this has long been understood to be a threat capable of causing extended power outages. (Figures 7 and 8 detail the likelihood of LPT collapse during GMD and EMP events, while Figures 9 and 10 show nuclear power plants in the same area as a hypothetical EMP over Columbus). It should be noted over half of the U.S.'s 99 commercial nuclear plants lie within this area. Were either a large scale (4600 nT) GMD or a modest (1-2 MT) HEMP event to occur, there is a high probability that offsite power to nuclear facilities would be lost due to LPT damage throughout the grid.

Complicating the matter is the long duration it takes to produce an LPT and the limited number of manufacturers nationwide. As previously stated, the completion loop for LPT design to manufacturing is approximately 18 months. However, this does not account for disruptions to shipping due to secondary effects of a potential EMP event, and no accurate estimates are available on how extensive shipping delays would be during an EMP crisis. Currently, there are approximately 2,000 extra-high voltage transformers in the U.S. and several hundred thousand

[84] DOE LPT Report, http://energy.gov/sites/prod/files/Large%20Power%20Transformer%20Study%20-%20June%202012_0.pdf.
[85] Fukushima, 5-6.
[86] Ibid.

lower voltage LPTs.[87] However only 500 LPT units per year were imported on demand to the U.S. between 2007 and 2011.[88] This means that many EHV LPTs and thousands of other lower voltage LPTs needed to repair the grid during either a large GMD or man-made EMP attack scenario would not be immediately available as present imports are by demand. According to most estimates it would take years to repair the damage, and that is assuming America's strategic competitors remain willing to import replacement LPTs with an understanding they face similar threats.

The DOE stated "Although the exact statistics are unavailable, global power transformer supply conditions indicate that the [United States'] reliance on foreign manufacturers is even greater for extra high-voltage (EHV) power transformers with a maximum voltage rating greater than or equal to 345 kV."[89] In other words, where large power transformers used at substations and electric generating facilities are concerned, repair will be heavily reliant on entities outside the U.S.. The greatest of these entities is China, whose LPTs production capability is nearly six times greater than the U.S..

An Overview of Nuclear Facilities

During the Fukushima disaster, the plant faced malfunctions and scenarios that were beyond design-basis and thus beyond the scope of operations manuals which direct steps to be taken during a total blackout event with no access to outside power.[90] Although the plants' automated systems initially functioned in a "textbook" fashion, loss of DC and AC power (a potential issue in an EMP scenario) resulted in a failure of the cooling systems of the plant. The emergency diesel generators would normally have supplied AC and DC power; however, these were washed out by the tsunami. The result was a Fukushima with no source of AC or DC power and the result of that was a stoppage of cool water pumps. As a consequence, reactors 1, 2, 3, and the

[87] DOE LPT Report, http://energy.gov/sites/prod/files/Large%20Power%20Transformer%20Study%20-%20June%202012_0.pdf.
[88] Ibid.
[89] Ibid.
[90] Fukushima.

spent fuel pool in reactor 4 overheated. Since the plant lacked AC and DC power and SCADA systems that would have informed control room engineers of core temperatures and pressures, there were two unfortunate side effects. First, without accurate readings, precious time was lost trying to determine the status of the reactors and spent fuel pools. During this time, pressure within the containment units was allowed to build unchecked. Ultimately, this condition made adding cool water and taking measures to cool the reactor difficult. Second, by the time engineers had a good read on the situation inside the reactors; radiation levels were already dangerously high. Thus, both the heat and radiation interfered with efforts to access the manual controls and relief valves designed to work as secondary safety features. Those manual valves that were reached malfunctioned. However, it was unknown because SCADA was offline. Reflecting on both Fukushima and TMI as case studies, it is clear manual controls can serve as a backup; but given the failure of automated systems, those assurances are quickly diminished.

It is important to study Fukushima because twenty-three U.S. nuclear power plants utilize this design. Even those facilities not incorporating Mark I reactors are subject to the same basic scenario—an event in which both AC and DC power fail at the plant. Therefore, it is reasonable to assume that *if* total station blackout occurs, similar problems will arise, as found by the NTTF.

Additionally, the age of our nation's nuclear plants is worrisome - the average being 37 years. Thus, many reactors are approaching their life expectancy of 40 years.[91] Combined with known design flaws such as a small containment size, Mark I reactors pose an even greater risk in the wake of cooling losses. Even with newer model Mark II and Mark III design improvements, containment breach is still a threat if cooling systems should fail due to lack of power, as occurred at Fukushima.

Emergency Diesel Generators

Currently, the NRC and the nuclear industry as a whole, rely almost exclusively on EDGs for emergency on-site power. There is reason to believe that faith in EDGs alone might be a fatal

[91] Jeff Donn, *How Long Can Nuclear Reactors Last? US, Industry Extend Spans,* 2011 Today News, June 28, 2011 at (2011), http://www.today.com/id/43556350/ns/today-today_news/t/how-long-can-nuclear-reactors-last-us-industry-extend-spans/#.VcbA9vlVikp (last visited Aug. 8, 2015).

mistake. First, per NRC Regulatory Guide 1.9 (revision 4 – dated March 2007) EDGs are regulated for performance that is intended for only design-based events.[92]

Further, EDGs have shown vulnerabilities to SCADA-based attack. In a project, called "Aurora," EDG testing was conducted by the Department of Homeland Security at the DOE's Idaho lab in 2007. [93] Fluctuations caused when SCADA systems were hacked in a controlled experiment resulted in the destruction of an EDG similar to those used in electric producing power plants. [94]

Although the experiment featured a cyber-attack, the same principal can be extrapolated to EMP or GMD events. The Aurora project used hacking to alter the timing of the diesel generator, ultimately destroying the engine.[95] In theory, an EMP pulse could damage the EDGs by shorting out the board, disrupting processors (refer to Christmas Study Short-fall list, item 11, sub-items a-d), or affecting the control room from which they are being operated. Figure 13 features components tested during the EMP Commission study compared to known parts of EDGs from MTU Onsite Energy – a supplier of EDGs to nuclear power plants for more than 50 years.[96] Note the similarities between the devices. However, without further testing (which has not been done) one can only speculate, based on the EMP Commission's preliminary testing and baseline resistance levels from Siemens, that there will a high possibility of disruption or damage to SCADA aboard EDG systems in the event of an EMP.

Summary

In the U.S., the present the legal and regulatory approach to nuclear power is anchored in industry efforts to maintain safety regulations implemented during the 1980s and a national security mentality relevant at the end of the Cold War.[97] This has been successful, in part, due to a campaign to brand nuclear power as a clean, safe source of energy. To their credit, the NRC

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[92] Ibid.
[93] Jeanne Meserve, *Sources: Staged Cyber Attack Reveals Vulnerability in Power Grid,* 2007 CNN, Sept. 26, 2007 at (2007), http://edition.cnn.com/2007/US/09/26/power.at.risk/index.html (last visited Aug. 8, 2015).
[94] Ibid.
[95] Jeanne Meserve, *Sources: Staged Cyber Attack Reveals Vulnerability in Power Grid,* 2007 CNN, Sept. 26, 2007 at (2007), http://edition.cnn.com/2007/US/09/26/power.at.risk/index.html (last visited Aug. 8, 2015).
[96] Emergency Diesel Generator Sets for Nuclear Power Plants (MTU Onsite Energy via YouTube 2013), https://www.youtube.com/watch?v=5MZtLQigYNs (last visited Aug. 8, 2015).
[97] Fukushima, 102.

and industry have demonstrated commitment to safety where design basis events are concerned. However, EMP and GMD are beyond design basis events. Once these occur, there are no guarantees and few strategies with which to cope.

There have only been a handful of nuclear disasters in history, and only one in the U.S. – TMI. It is therefore understandable from an economic standpoint that industry is resistant to change. However, this inertia has given rise to a complacent regulatory climate absent adaptive and progressive analysis. More than 30 years lapsed since this topic was last openly addressed. Unfortunately, the assumptions borne of the highly questionable 1982 report continue to misinform decision makers even as recent as 2015. Despite these challenges and an NRC and industry galvanized to maintain the status quo, there are signs of progress.

Some push for increased standards and regulations has occurred since Fukushima. However, these efforts have been met with a tepid response from the nuclear industry. In an effort to stave off costly infrastructure updates, the industry responded by holding out the FLEX, a plan that is both impractical and dangerous due to an over reliance on a functioning national infrastructure.

Congress recently found, "The current strategy for recovery leaves the United States ill-prepared to respond effectively to an EMP attack that would potentially result in damage to vast numbers of components nearly simultaneously over unprecedented geographic scale."[98] As a result, 31 (bi-partisan) members of the House sponsored the Secure High-voltage Infrastructure for Electricity from Lethal Damage Act (or the SHIELD Act), to create a mechanism to address the nationwide EMP risk. The Act sought to create a mechanism whereby the President of the United States (POTUS) along with a specialized commission could designate certain areas and nodes critical to the U.S. infrastructure and security. The Act also provided the POTUS the authority to compel enterprises both public and private to protect key elements of the grid.

[98] Secure High-Voltage Infrastructure For Electricity From Lethal Damage Act (hereafter "SHIELD Act), H. R. 2417, 113th Cong.. https://www.congress.gov/bill/113th-congress-house-bill/2417/text, (last visited: Jun. 10, 2015).

Most importantly, the SHIELD Act would have conferred upon the U.S. Federal Energy Regulatory Commission legal authorities, which it currently lacks, to require the North American Electric Reliability Corporation and the electric power industry to protect EHV transformers, SCADAS, and other critical components of the bulk power system from natural and manmade EMP. Moreover, if SHIELD were enacted and implemented, by protecting the bulk power system, nuclear reactors would have been protected from the scenario of a nationwide protracted blackout.

The Congressional EMP Commission estimated that the national electric grid could be protected from natural and manmade EMP for about $2 billion and that implementation, on a non-emergency basis, would require 3-5 years. However, lobbying by the electric power industry kept SHIELD from coming to a vote before the House Energy and Commerce Committee for years, until the bill died.

In November 2015, the House passed by unanimous consent the Critical Infrastructure Protection Act (CIPA--HR 1037), which bill requires the Department of Homeland Security to establish a new National Planning Scenario focused on EMP. All federal, state, and local emergency planning, training, and resource allocation is based on the National Planning Scenarios—so CIPA will for the first time require emergency planners and first responders at all levels of government to be EMP educated and begin preparing to survive and recover the nation from an EMP catastrophe. CIPA further requires DHS to develop plans to protect the electric grid and other critical infrastructures from natural and manmade EMP, to evaluate existing technologies and help develop new technologies for EMP protection, and to launch pilot projects to encourage the protection of the electric grid and other critical infrastructures. CIPA currently awaits action by the Senate.

Conclusions

The U.S. must address 21st Century problems with 21st Century prevention-based mitigation strategies that are part of a holistic and commonsense approach. This study contends that although the threat to EMP/GMD and its likely impacts on nuclear power stations have been known for some time, both internal and external political pressures have ensured the regulatory and technological status quo for more than three decades.

There are steps that may be implemented to significantly reduce our vulnerability to EMP and GMD including the addition of requirements to sustain stations, hardening, filters and development of better early warning and detection systems that would allow for grid isolation and shutdown before impact. However, hardening the nation against an EMP or major GMD event will require a total effort directed not only toward critical infrastructure and national resources, but also those that beckon to greater individual and community responsibility relating to issues of sustainment. With that in mind, we recommend a holistic approach that strengthens both our nuclear infrastructure and individual communities until a total solution is realized.

In a world where America's adversaries are increasingly innovating, developing, adapting, and accessing conventional and asymmetric weapons capabilities, our nation must make grid protection a top priority. However, the theoretical dichotomy between America's grid and nuclear power stations and research reactors must be expunged. Our power grid is part of a total system – a system that is required to ensure a safe and prosperous United States, and all of it must be safeguarded if we take our national security seriously.

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Appendix – A - Figures

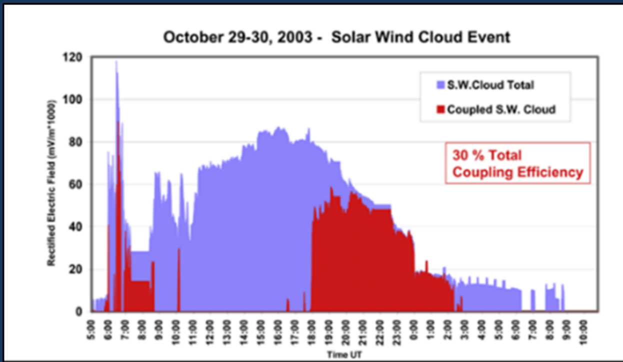

Figure 1: Simpson, Sarah. "Massive GMDs Inflict Little Damage on Earth." Chart depicting coupling efficiency during 2003 Halloween Storms http://onlinelibrary.wiley.com/doi/10.1029/2003SW000042/full;jsessionid=FF860B5019A6B84641A219CD5FDC08A6.f03t04?wol1URL=/doi/10.1029/2003SW000042/full&regionCode=US-TX&identityKey=15214635-1122-4c46-9c50-0629fa1eceb8&isReportingDone=false

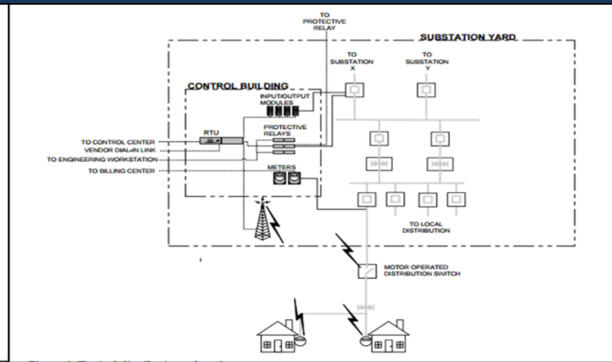

Figure 2: Understanding the Interconnections of SCADA systems and the Electric Grid: This model illustrates the relationship between SCADA systems and a typical transmission distribution substation. This model comes from the document "Introduction To SCADA Protection And Vulnerabilities," by Ken Barnes and Briam Johnson. The report was prepared by the Idaho National Engineering and Environmental Laboratory for the Department of Energy in 2004. http://www5vip.inl.gov/technicalpublications/Documents/3310860.pdf

Figure 3: Darlington Nuclear Power Plant: Control room featuring multiple consuls where data fed from SCADA systems is relayed to control room workers. Note that many of these systems failed during the long power duration issues faced at Fukushima. The 2003 Northeast Blackout did not see widespread control room issues, however one automated process failed to perform from SCADA based controls in the Fermi 2 nuclear plant in Toledo, OH. It took 26 hours to resolve the issue.

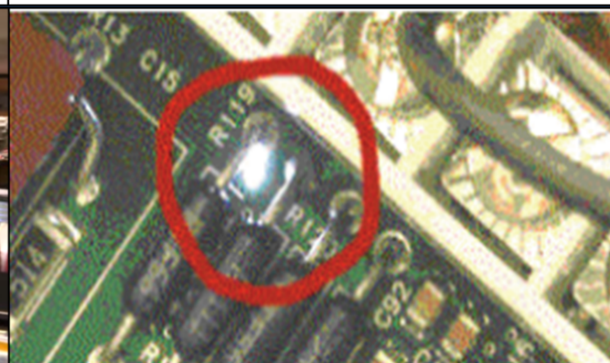

Figure 4: Physical Damage to Circuitry from EMP Field Testing: Most electronics can expect to receive similar damage even a low levels of EMP stress according to the 2008 EMP Commission Report.

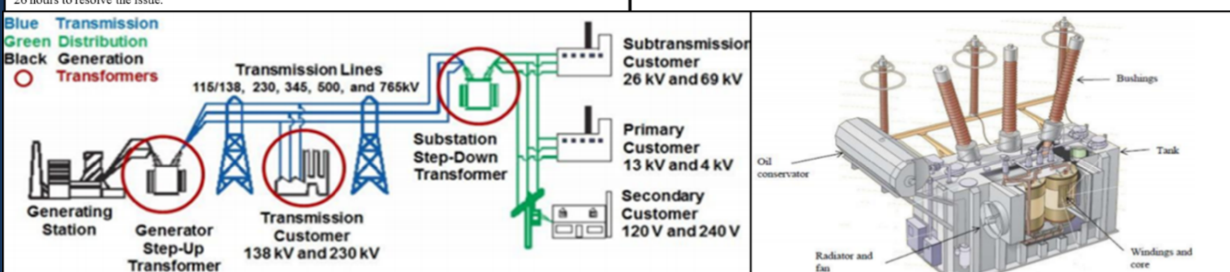

Figure 5: Compilation explaining the basic role of LPTs in the power grid and accompanied by an illustration of the parts and design of one type of extra-high voltage (EHV) LPT system. These graphics were assembled from a 2012 DOE document entitled: *Large Power Transformers and the U.S. Electric Grid.*

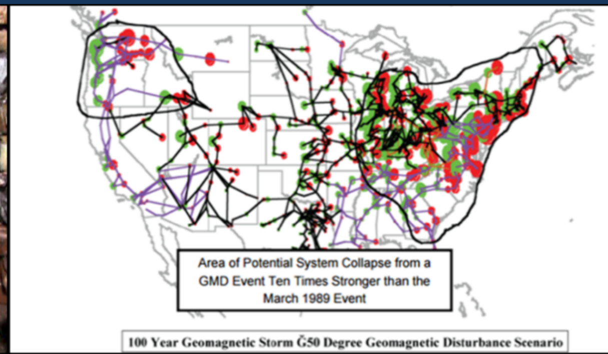

Figure 6: (Right) This is a picture of the Salem New Jersey Nuclear Plant GSU Transformer (~12mVA, 500/22kV single phase transformer) and permanent damage caused by the March 13, 1989 Geomagnetic Storm. Photos courtesy of PSE&G, and found in the 2008 EMP Commission Report. **(Left)** Similar damage has been observed on this transformer from South Africa.

Figure 7: This simulation is based off of findings by the *High-Impact, Low-Frequency Event Risk to North American Built Power System* Report (June 2010). The area depicted shows simulation results indicating the patterns of GIC flows in the U.S. grid for a -4800 nT/min field disturbance. The lower the number the more destructive. For historical comparison the Carrington Event in 1859 and the Geomagnetic Storm of 1921 produced nT values as low as -1200 to -1600 nT; roughly four times as destructive as the depicted estimate.

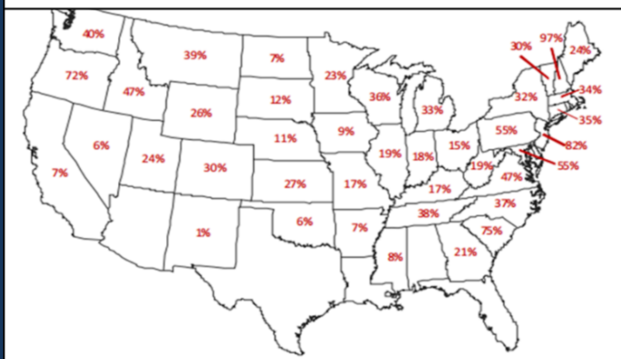

Figure 8: This map is based off of the event depicted in Figure 7, also from the *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System* Report (June 2010). The map shows the "At-Risk EHV Transformer Capacity by State," with higher percentages indicating areas where power outage could last multiple years.

Figure 9: This map, also from the *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System* Report (June 2010), illustrates the affected area from the E1 phase of an EMP detonated at a height of 170 miles above Ohio. Note the affected areas fall within the same general areas as those associated with probable failure during a geomagnetic storm event as in Figures 7 and 8. Also, note that the affected area would encompass many of the nuclear power plants depicted in Figure 11.

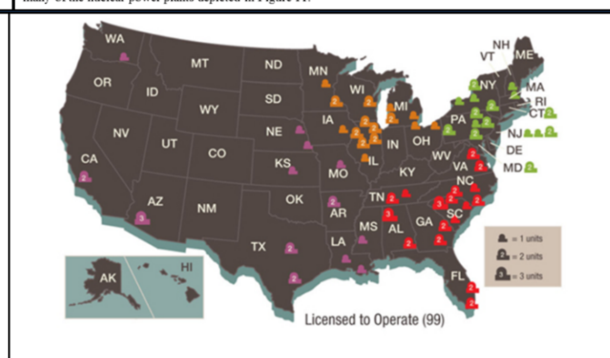

Figure 10: This map also from the *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System* Report (June 2010), illustrates the "1765 EVH substations at 345 kV and higher" with 83% exposed to the E1 burst from Figure 9. Again, note the affected areas also fall within the same general areas as those associated with probable failure during a geomagnetic storm event as in Figures 7 and 8. Also, note that the affected area would also encompass many of the nuclear plants in Figure 11.

Figure 11: This map from the Nuclear Regulatory Commission, illustrates the 99 operational nuclear power plants in the United States. Experimental reactors, test facilities, and nuclear reactors in cold status are not identified. Note the proximity, in relation to figures 7-10, to areas affected by the E1-E3 pulses of either a geomagnetic storm or an EMP event.

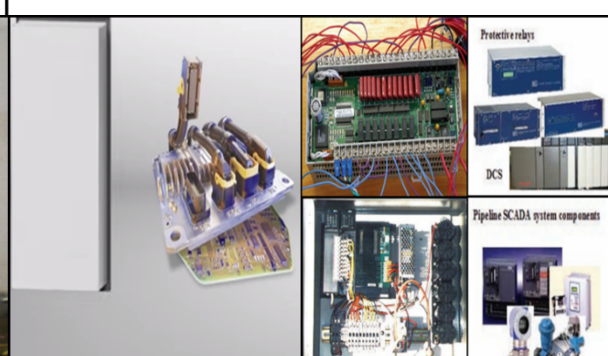

Figure 12: Fukushima's Unit 4 after a hydrogen explosion rips apart the 3rd, 4th, and 5th floor. Photo courtesy of Forbes: http://www.forbes.com/sites/williampentland/2013/12/30/yakuza-gangsters-recruit-homeless-men-for-fukushima-nuclear-clean-up/

Figure 13: (Left) SafeDEC Digital Engine Governor by MTU Onsite Energy, used in EDGs in several nuclear power plants. **(Right)** SCADA systems tested by the EMP Commission in 2008.

Figure 14: Historical Geomagnetic Storms - Measured in Nano Teslas (nT)				
Date	Duration	Peak nT-Dst	Title (If Named)	Effects
23-Jul-2012	N/A - Miss	~ -1200	2012 Superstorm	*Missed Earth by ~ 9 Days
20-Nov-2003	1 Days	-422		
29-Oct-2003	3 Days	-383	Halloween Storms	*WAAS Down 30 Hours *Severe Satellite Disruptions
5-Nov-2001	2 Days	-292	Not Named	*Minor Disturbance Noted in Japan
30-Mar-2001	3 Days	-387	Not Named	*Minor Disturbance Noted - Location Not Specificd
15-Jul-2000	1 Days	-301	Bastille Event	Per NASA This Event Was Capable of Producing: *Single-event Upsets, *Noise in Imaging Systems *Permanent Damage to Exposed Components/Detectors *Decrease of Solar Panel Currents. *Expose Air Travelers at High Latitudes to Low Levels of Radiation - Brief Chest X-ray
09-Mar-1989	5 Days	-589	Quebec Blackout	*6 Million People Lost Power *4 Satellites Damaged *Several Reports of Electical Damage to Power Plant Equipment
01-Sep-1859	2 Days	-1760	Carrington Event	*Telegraph Machines Burst Into Flames *Arura Borialis Seen in Cuba *Although a Lack of Technology Minimized the Event Many Scientists Insists This Event Would Devestate Modern Society
Sources:				
http://www.geomag.usgs.gov http://web.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-319.pdf http://science.nasa.gov/science-news/science-at-nasa/2000/ast14jul_2m/				

Historical EMP Testing Measured in Kilovolts per Meter (kV/m)				
Date	Ordinance and Duration	kV/m Field Strength	Title (If Named)	Effects
09-Jul-1962	*1.4 Megaton Nuclear Bomb *Approximately 400km Altitude *>60 seconds	10-50 kV/m When Detonated at 250 Miles Altitude	STARFISH PRIME	Electrical Power Failures Over 900 Miles from Point of Origin, Car Stalls, Communications Disruptions, and Probable Failure of Most Electronic Devices (When Data is Extrapolated to Modern Electronics
Sources:				
http://fas.org/spp/starwars/congress/1997_h/has17010_1.htm				

End of report: