

INTRODUCTION TO THE ELECTROMAGNETIC PULSE ISSUE IN THE NUCLEAR POWER INDUSTRY

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ABSTRACT

One of the greatest threats to the United States today is a widespread and long-term disruption to the power grid resulting from a high-altitude and/or electromagnetic pulse (EMP) Nuclear Weapon. Almost all-digital operations for critical infrastructure that rely on electricity would break down without electricity to sustain them. A high-altitude electromagnetic pulse (HEMP) resulting from detonation of a nuclear weapon or an EMP from a natural solar disturbance not only poses potential risks to digital instrumentation and controls (DI&C) systems used to safely shut down and maintain nuclear power plants (NPP) in a safe operating condition, but can also adversely impact their ability to provide power once the electrical grid is restored. This paper provides an introduction to the following:

- The HEMP issue
- A summary of the research done by various agencies over the years
- Potential HEMP risks to NPPs and their interface to the electric power grid
- Mitigative measures recommended by recent research
- A methodology nuclear plant operators could employ to begin identifying potentially vulnerable areas that may require mitigation
- Existing industry standards used to ensure the electromagnetic compatibility (EMC) of new equipment installed in the plants against common electromagnetic threats
- Potential vulnerability gaps between those standards and mitigation needed for an EMP event
- Recommendations on how to modify plant standards or site EMC test specifications to address and mitigate EMP threats

Note: Information obtained from unclassified documents available to the general public. This paper is a culmination of information derived from the References.

Key Words: EMP, HEMP, Electromagnetic, Pulse, Threat

1 INTRODUCTION: THE HIGH-ALTITUDE ELECTROMAGNETIC PULSE ISSUE

A 2017 Department of Homeland Security (DHS) Report (Reference 1) explains that communication, transportation, food, housing, water, and healthcare are all dependent upon a reliable power grid; more importantly, the DHS report states that “as reliance on electricity continues to grow, a significant disruption to the electric grid may put lives, the economy, and the environment in danger.” Global commerce depends on computers, cell phones, and the Internet. Since energy is the foundation of the modern world, long-term and widespread power outages would obviously endanger civilization. The atomic age quickly brought the development of nuclear bombs and raised the specter of a HEMP to threaten the stability of the national electric grid. While commercial NPPs are not required by law to include HEMP protection, the United States Nuclear Regulatory Commission (U.S. NRC) studied this issue in the 1980s, exploring the possibility of a HEMP adversely impacting a nuclear power plant’s ability to achieve and maintain safe shutdown. In

1983, the NRC published in (NUREG/CR-3069 (Reference 10)) its study conclusions that a HEMP would not threaten the ability of NPPs to achieve and maintain safe shutdown conditions. The NRC completed follow-up studies (Reference 24) in 2009 and 2010 to consider the transition of analog instrumentation and controls (I&C) systems to digital I&C systems since they can be more vulnerable to the effects of a HEMP. The new studies also incorporated at a high level the effect of solar-induced events, and the NRC's conclusions remained unchanged. However, despite the NRC's conclusions, this paper will describe in later sections the wider implications that may remain unaddressed regarding NPPs returning to reliable power production and interface of the plants to a power grid that may have been degraded.

Eighty-five years before the world's first nuclear bomb (Trinity) was detonated, and over 130 years before the invention of the Internet web browser, the world experienced an incredible and disruptive electromagnetic incident called the Carrington Event (North Atlantic Electric Reliability Corporation (NERC) Geomagnetic Disturbance (GMD) Report, Reference 2). Named after the British astronomer who observed it, the solar activity of 1859 led to the strongest geomagnetic storm on record, which damaged telegraph systems all over the world. Some telegraph operators discovered they could continue to transmit only if they disconnected their power sources and let the system run on the "auroral" currents induced in the wires from the supercharged atmosphere. Impacts from the storm were limited given the state of technology at the time; today modern society is far more vulnerable to the effects of a significant GMD event due to its reliance on electricity and technology. A more recent significant event (NERC GMD Report, Reference 2) occurred in 1989, when a geomagnetic storm collapsed the Hydro-Québec power grid in under two minutes, resulting in the loss of electric power to more than six million people for nine hours in Canada. Blackout to part of the Hydro-Quebec system was caused when seven static voltage-amps' reactive compensators tripped due to increased levels of harmonics on the power lines, which led to voltage depression and frequency increase on the system. Soon afterwards, the rest of the grid collapsed because of the abrupt loss of load and generation.

In 1990, the NRC released Information Notice (IN) No. 90-42 (Reference 3), "Failure of Electrical Power Equipment Due to Solar Magnetic Disturbances." It described other solar storms that occurred in 1989 that resulted in damaged substation equipment and transformers at three NPPs. The notice explained that "auroral" currents establish geomagnetically induced currents (GICs) that can damage grounded wye-connected transformers and degrade the transmission system. The notice alerted plant operators of the potential for such an event to become a precursor to a station blackout (SBO) or partial loss of offsite power (LOOP), but it did not issue new requirements. U.S. NPPs later implemented measures in response to the 2011 Fukushima events to cope with a long-term loss of power, *but these efforts were focused on maintaining safe shutdown, not re-establishing a connection to the power grid.* Damaged power transformers, if suitable replacements are not readily available, could keep a plant offline for months. Powerful geomagnetic disturbances increase demand to replace the simultaneous loss of numerous large power transformers, which strains the supply chain and aggravates the problem. In 2003, a solar storm impacted and resulted in hot-spots and/or damage to the generator step-up (GSU) transformers at the Seabrook and Point Beach NPPs. For these plants, abnormal operating procedures (AOPs) were developed to install clamp-on hall effect DC ammeters and data loggers to monitor GICs during warnings of an impending GMD. Those warnings gave the plants the opportunity to decrease power, and thus temperature inside the transformers, to lessen the impacts from GMD induced hot-spots.

In 2019, the President issued Executive Order 13865 (Reference 4), "Coordinating National Resilience to Electromagnetic Pulses," to address the threats to the national power grid by man-made or naturally occurring EMPs. As a result, the DHS began collaborating with several federal agencies, including the NRC, to identify the greatest risks to critical infrastructure and develop ways to mitigate those risks and restore power to the grid. In parallel, the Electric Power Research Institute (EPRI) released reports (References 5 and 6) summarizing its research and findings of a three-year effort to investigate the same issue. Although the U.S. Government has also investigated the impact of a 100-year superstorm, the

experience to date is from events that may be orders of magnitude smaller in scope and less severe than that expected from a HEMP.

Detailed HEMP testing has been performed on military communication and weapon systems, but not on high-voltage systems essential to electricity generation, transmission, and distribution. Observed HEMP impacts from the high-altitude atmospheric nuclear tests conducted by the U.S. in 1958 and 1962 (Starfish Prime Test) included system effects observations with little or no available information on HEMP stress levels. Existing test data used in developing military standard HEMP protection benchmarks was used as a baseline to identify gaps in testing, hardening principles and possible protection strategies. The Soviet Union's K project nuclear HEMP test series was a group of five (5) nuclear tests conducted in 1961-1962, using 1.2 kiloton to 300 kiloton warheads. Soviet scientists instrumented a 350-mile section of telephone line in the area they expected to be affected by the nuclear detonation in order to measure the EMP effects. During the test, measured currents of 1500 to 3400 amperes resulted in all fuses blowing, all overvoltage protectors firing and the EMP fusing all 350 miles of the monitored overhead telephone line. The same test caused the destruction of the Karaganda power plant and shut down 620 miles of shallow-buried power cables between two cities. After the 1991 collapse of the Soviet Union, Russian scientists communicated informally the level of this damage from the high-altitude nuclear EMP test to scientists in the U.S.

2 SUMMARY OF PAST RESEARCH BY VARIOUS AGENCIES

The effects of HEMP on the electrical power system per DHS Strategy Report (Reference 7) are fundamentally partitioned into its early (E1), middle (E2), and late-time effects (E3) components (See Figure 1 on page 4 below). The net impact on the electric power grid includes the interaction of all three pulses, occurring nearly simultaneously over a large geographic area. The strength and area coverage of HEMP physical effects depends on the warhead type and yield, as well as the altitude and latitude of the detonation. A nuclear device detonated at high altitudes between 30 and 400 kilometers would generate an EMP with amplitudes in the tens of kilovolts per meter with a radius of effects from hundreds to thousands of kilometers, and represents the greatest potential for severe impacts to the nation's critical infrastructure.

E1 EMP – Per the Commission on Critical National Infrastructures (Reference 8) and EPRI Technical Report 3002014979 (Reference 6), the early-time EMP, or E1, is created by gamma-ray interaction with stratospheric air molecules, and is a freely propagating field with a rise time in the range of less than one to a few nanoseconds amplitude on the order of tens of kV/m (up to 50 kV/m at the most severe location on the ground). E1's power spectrum frequency is in the 10s to 100s of megahertz, enabling it to couple to electrical and electronic systems in general, regardless of the length of their penetrating cables and antenna lines. Induced currents range into the 1000s of amperes. E1 damages or disrupts electronics such as supervisory control and data acquisition (SCADA) and digital control systems (DCS), as well as programmable logic controllers (PLC) and communications. This disrupts control systems, sensors, communication systems, protective systems, generator systems, fuel systems, environmental mitigation systems and their related computers, as well as the ability for them to be repaired. The E1 pulse also causes flashovers in the lower-voltage distribution system, resulting in immediate broad geographic scale loss of electrical load and requiring line or insulator replacement for restoration.

E2 EMP – Per References 6 and 8, the intermediate-time EMP, or E2, is produced by delayed gamma rays and neutron-induced currents, and is similar in frequency to lightning, but vastly more widespread, like thousands to millions of simultaneous lightning strikes, even if each strike is at lower amplitudes than most naturally occurring lightning. An E2 EMP has an electric field pulse amplitude of 0.1 kV/m and duration of one to approximately ten milliseconds. The electrical power system has existing protective measures for lightning; however, the impact of this many simultaneous lightning-like strikes over an extremely large geographic area may exceed those protections. The most significant risk, however, is synergistic because the E2 pulse follows on the heels of the E1. Thus, where E1-induced damage has

circumvented lightning protection, the E2 impact could pass directly into major system components and damage them.

E3 EMP – Per References 6 and 8, the late-time EMP, or E3, is caused by the distortion of the earth’s magnetic field lines due to the expanding nuclear fireball and rising of heated and ionized layers of the ionosphere. The change of the magnetic field at the earth’s surface induces currents of hundreds of thousands of amperes in long conducting lines (a few kilometers or greater) that damage components of the electric power grid as well as connected systems. E3 follows E1 and E2 and may last for a minute or more. It is a low-frequency (below 1 Hz) pulse with amplitude on the order of tens of V/km with duration of one second to hundreds of seconds. The E3 pulse is similar in many respects to GMD effects induced by solar storms. Solar storms are known to cause serious damage to major electrical system components at much lower levels than the possible E3 impact. This damage has been incurred in spite of functioning, in-place protective systems. Given the preceding E1 and E2 pulse damage to the protective systems and other system components, damage from E3 to unprotected major system components is virtually assured.

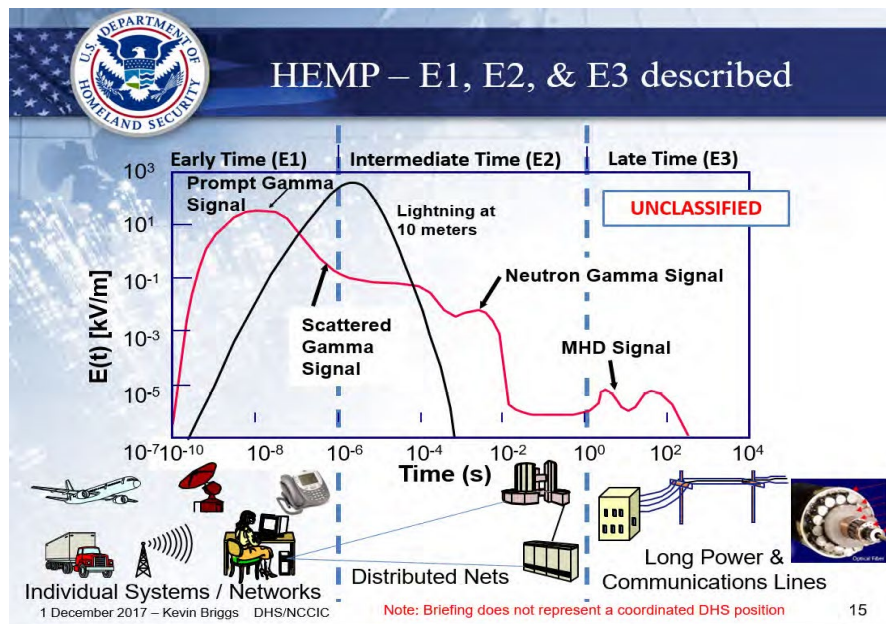


Figure 1. Generic HEMP Waveform: EMP Protection and Resilience Guidelines (Reference 11)

Each of the three EMP modes of system impact is sufficient by itself to cause disruption and probable functional collapse of large portions of the interconnected electrical power system. The Commission on Critical National Infrastructures (Reference 8) assessment stated that functional collapse of the electrical power system region within the primary area of assault is virtually certain. Furthermore, widespread functional collapse may result even from a small weapon with a significant E1 component. While stopping electrical supply over a broad geographical area nearly instantaneously is damaging, it is the time it takes to restore service that is important, assuming restoration is possible, which itself may be questioned in some instances.

3 POTENTIAL EMP RISKS SPECIFIC TO NUCLEAR POWER PLANTS AND THEIR INTERFACE TO THE ELECTRIC POWER GRID

According to the U.S. Department of Energy (DOE) Electromagnetic Pulse Resilience Action Plan (Reference 9), HEMPs have demonstrated potential to disrupt, damage, or destroy a wide variety of electrical and electronic equipment. This damage can occur anywhere on the electrical grid, including Transmission Lines, Distribution and Generation. Most conversations about EMP focus on either E1, the

large initial energy pulse, or E3, the smaller and longer duration effect. The E1 waveform is a fast pulse that disrupts systems in general, including long-line electrical systems, computers, sensors, relays, and electronic-based control systems. The E3 waveform is a low-amplitude, long-duration pulse, persisting for hundreds of seconds that induces currents in long power and communication lines, destabilizing or damaging connected equipment such as transformers and solid-state communication line drivers. The currents in these long lines can aggregate to become sufficiently large (minute-long, ground-induced currents [GIC] of hundreds to thousands of amperes) to damage major electrical power system components. With respect to transformers, which are more difficult to replace quickly, this quasi-direct current carried by all three phases on the primary windings of the transformer drives the transformer to saturation. This saturation, consisting of harmonics and a surge in reactive power, can result in case heating, over-currents in capacitors, damage to surrounding components and potential fires. The reactive power flow adds to the stresses on the grid. This is the type of damage experienced by the GSU transformers at the Seabrook and Point Beach NPPs described earlier.

In the EMP Commission Report (Reference 8), the Federal Energy Regulatory Commission (FERC) states that it lacks regulatory power to compel NERC and the electric power industry to protect the grid from natural and nuclear EMP and other threats. The NRC has regulatory power to compel the nuclear power industry to incorporate nuclear reactor design features to make nuclear power safe; however, to date, the NRC has not incorporated EMP survival criteria into design regulations and has not required that spare transformers or emergency diesel generators (EDGs) be certified as EMP-protected. Moreover, testifying before a House Energy and Commerce Subcommittee in 2017, the Chief Executive Officer of NERC expressed opposition to any new FERC legislative authority to strengthen or directly promulgate any new grid reliability standard that NERC had not already proposed, thereby undermining the FERC's ability to protect the U.S. electric power grids from EMP attack. *Also, the GMD standards proposed by NERC, which FERC had adopted to date, substantially underestimated the magnitude of historical and future GMDs. The EMP Commission's July 2017 recommendation (Reference 8) that government agencies and industries adopt new more realistic standards of 85 V/km to protect critical national infrastructures from damaging E3 EMP heave fields has not yet been imposed.* Extensively tested, performance-proven technologies for EMP hardening have been developed and used by the Department of Defense (DOD) to protect critical military systems for over 50 years, and can be affordably adapted to protect electric grids and other critical infrastructures at low-cost relative to that of an EMP catastrophe. However, no DOD standards for protecting the grid against nuclear or non-nuclear EMP weapons have been proposed or adopted. Therefore, that results in continued vulnerability of power generating facilities (including NPPs) and the grid to EMPs and HEMP. Because protection of every component of the electric power grid is impractical, the DOE started in 2016 to work with FERC, DHS, and industry to review and evaluate methodologies used to identify critical, and potentially susceptible, assets, nodes, and systems—and their failure consequences. The strategy being developed is a risk-based approach to identify the subset of systems and components that are both of critical importance to system operation and most susceptible to EMP impact. This effort has several milestone dates that will conclude with issuance of a report and a project timeline to assess the feasibility of running field tests of different hardening techniques for a set of EMP scenarios by 9/30/2021, according to the timeline outlined in the DOE Electromagnetic Pulse Resilience Action Plan (Reference 9).

Although protection engineering practices are well-known and demonstrated for communication and control equipment and facilities, the same is not true for high-voltage substation, generation plant equipment and other critical national infrastructure, which remain largely unprotected from EMP threats. The DOD's protection standards may not be affordable for some electric power grid facilities and systems, so although effective practices are being identified and promoted, focus at the present is on the most critical and vulnerable components and assets critical for a restart of an electric power grid. Research and tests are being conducted to harden substations and generation stations to a range of EMP scenarios, and evaluate the effectiveness of hardening measures (such as use of high-speed compression networks). EMP damage is often not highly visible, putting a premium on electronic system failure diagnostics.

While many large utilities have black-start plans and capabilities based on more typical triggering events, the black-start capabilities are usually not themselves protected from EMPs. It is also the case that in the event of a grid failure collapse due to an EMP, it is likely that the telecommunications needed to restore the grid may also be inoperable. Finally, much of the electrical equipment powered by the affected portion of the grid may similarly be damaged and will affect the availability of the load necessary to balance the system when restarting generation stations. The interaction of these circumstances will create a unique set of challenges that are now only poorly understood.

The NRC study performed and documented by NRC NUREG/CR-3069 (Reference 10) examined the interaction of the EMP from a HEMP with commercial NPP systems, mainly TVA's Watts Bar Nuclear Plant. The potential vulnerability of systems required for safe shutdown of a specific NPP was explored. EMP signal coupling, induced plant response and component damage thresholds were established using techniques developed over several decades under Defense Nuclear Agency (DNA) sponsorship. A limited test program was conducted to verify the coupling analysis technique as applied to an NPP. The results were extended, insofar as possible, to other NPPs. Based upon the analysis, the study concluded that: (1) Diffuse fields inside Seismic Class I buildings are negligible; (2) EMP signal entry points are identifiable; (3) Interior signal attenuation can be reasonably modeled; (4) Damage thresholds, even for equipment containing solid-state components, are high; (5) EMP-induced signals at the critical equipment in the example plant are much less than nominal operating levels, but plant topology and cabling practice have a strong influence on responses; and (6) 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 safe shutdown.

Although the study concluded that it was unlikely that an EMP event would prevent NPPs from achieving safe shutdown, the study also stated that there were several questions raised that required more investigation and evaluation.

The E3 EMP was not considered extensively because this threat is expected to be confined to the main output transformers. Therefore, the most drastic response of the power system would likely be a disconnection of the transformer from the transmission grid as a result of either damage to the transformer itself by thermal effects or initiation of the transformer protective circuitry. Neither of these occurrences would affect the ability of safety systems to shut down the plant. This study addressed only selected items of the safe shutdown systems, and circuit parameters were evaluated at only one frequency (1 MHz). Certain circuit parameters will vary with frequency; for example, the impedance to ground through the shunt paths (capacitors or capacitive coupling) decreases with frequency while the component thresholds increase as the square root of the frequency. It should also be noted that experience suggests that EMP-induced failures of passive components (e.g., resistors, capacitors, chokes, etc.) could lead to circuit damage thresholds comparable to those estimated for solid-state components. System upset was not addressed as part of this study. If the EMP Coupling Analyses reveals that significant EMP-induced signals are possible at the points of concern, that is signal levels on the order of circuit logic levels, the potential for system upset may exist and should be investigated if upset is of concern. Additionally, if localized voltages are high (on the order of several kV or more), arcing or other dielectric breakdown of passive components should be considered as noted earlier. To determine arcing thresholds analytically is intractable, and any such investigation would require the support of an engineering testing program.

In addition, three additional plants, each of different design, were surveyed to determine whether generic features common to these plants are sufficiently analogous to the Watts Bar Nuclear Plant to allow those results to be extended to NPPs in general. The three plants visited were the Catawba Nuclear Station of the Duke Power Company, the Clinton Power Station of the Illinois Power Company, and the Palo Verde Nuclear Generating Station of the Arizona Public Service Company. From evaluation of data, it was concluded that significant variations in responses at penetration interfaces can exist at NPPs, and therefore, the Watts Bar results are not necessarily indicative of NPPs in general. Process control transmitters of the Rosemont 1153 type were evaluated, and many of their signals passed through 1/1 isolation before being

sent to bistable trip units in the plant protection system rack; however, since no information such as schematics was available, circuit damage thresholds could not be determined. In addition, some transmitters were not sufficiently isolated and were excluded from analysis. Power for the process instrumentation racks was supplied by the 120 VAC, Class 1E vital bus. This power is used by a Foxboro power supply, which then outputs a regulated DC similar in function to the Foxboro regulated DC power supply at Watts Bar. Schematic information was not available to verify that this was the same power supply; therefore, extension of the calculated Watts Bar results cannot be assumed.

The data obtained in the study was insufficient to make a definitive statement on the generic EMP susceptibility of NPPs. While it is true that types of equipment similar to Watts Bar equipment items were found at the various plants, not enough evidence was available to state with authority that the Watts Bar susceptibilities are representative of the full spectrum of NPP designs. It was demonstrated, however, that the methodology described herein provides a process by which this type of comparison can be performed. A vulnerability assessment for all three plants was not attempted since plant topology and cabling practices have a strong influence on EMP-induced response. Therefore, discretion must be used in extending the example plant results to other plants. However, in view of the similarities in the design and construction of NPPs and based upon the conservatisms in the analyses, it was the technical judgement of the study team that the safe shutdown capability of NPPs in general would survive the postulated EMP event. However, greater uncertainty is associated with this judgement when applied to those plants that include design features that enhance coupling with incident EMP (e.g., unshielded overhead or buried electrical cables between the main building and satellite structures).

The study noted four areas that may merit further consideration in order to evaluate the response of a typical NPP to an EMP and are discussed separately in the following paragraphs.

Baseline Completion: The damage threshold analysis method described here provides a reasonable vehicle by which to determine whether in-depth studies should be conducted of other plants. More complete analysis of equipment not covered will provide a better baseline for answering the question of the extensibility of the Watts Bar results to other plants.

Other EM Specifications: Other EM specifications that presently are being applied to nuclear systems (e.g., EMI, lightning, etc.) can afford some protection from EMP. These specifications should be investigated to examine EMP mitigation implications inherent in the compliance to these specifications. An example would be to further investigate IEEE-STD-472 (Reference 21) tests and further explore whether a provision for a lower bound on an EMP threshold can be determined.

Engineering Tests: It was determined in this study that circuit damage thresholds were mostly high. It is clear, especially in the cases of calculated voltage thresholds greater than 2-3 kV, that arcing or other dielectric breakdown of passive components may be expected to occur first given sufficiently high driving signals. Analytic determination of the levels at which arcing phenomena occur may not be practical, so if further investigation of the circuit damage threshold mechanisms is desired, the support of an engineering test program is required and, thus, recommended.

EMP-Induced Upsets: The nuclear power industry and the NRC have been, and continue to be, concerned with the potential plant operational upsets that have been observed to occur due to electrical transients from various sources, such as switching, inductive surges, lightning, and other sources of electromagnetic interference. The results of the previous and ongoing studies relating to transient-induced operational upset combined with the evaluation of current or proposed transient tolerance specifications will permit the identification of the unique upset implications of an EMP threat and the identification of areas of investigation (including required tests) that should be considered if it is found that EMP transients can produce upset modes that are unlikely to be mitigated as a result of existing studies or specifications.

4 MITIGATIVE MEASURES RECOMMENDED BY RECENT RESEARCH

NPP operators could employ the previously noted steps to begin identifying potentially vulnerable areas that may require mitigation and then improving, extending, and exercising recovery capabilities. The next step would be to develop procedures for addressing the impact of such attacks to identify weaknesses, develop and provide HEMP response training for personnel, and coordinate all activities with appropriate agencies and industry. The first step in recovery is identifying the extent and nature of the damage to the system and then implementing a comprehensive plan with trained personnel and a reservoir of spare parts to repair the damage. Damage is defined as anything that requires a trained person to take an action with a component, which can include simply rebooting all the way to replacing major internal elements of the entire component. Four goals of further evaluation and analysis needed are described below:

1. Protect high-value assets through hardening. Hardening, providing for special grounding, and other schemes are required to ensure the functional operation of protection equipment for large, high-value assets, such as transformers, breakers, and generators, and to protect against sequential, subsequent impacts from E2 and E3 creating damage. Existing shielding in some electronics, despite not being specifically designed to do so, may protect against EMP. Only some combination of shielding, grounding, and filtering, combined with verification testing, can ensure that electronics will function through an E1 EMP.

2. Ensure adequate communication assets are dedicated and available to the electrical system operators so that damage during system collapse can be minimized; components requiring human intervention to bring them on-line are identified and located; critical manpower can be contacted and dispatched; fuel, spare parts and other commodities critical to the electrical system restoration can be allocated; and the ability to match generation to load and bring the system back on line can be provided.

3. Protect the use of emergency power supplies and fuel delivery and provide for their sustained use as part of the protection of critical loads. Require the emergency generator start, operation, and interconnection mechanisms to be EMP hardened or manual without microelectronic dependence.

4. Application of four (4) EMP Protection Levels for Infrastructure and Equipment (EMP Protection Guidelines Reference 11), which are briefly summarized below:

Level 1 (Long Outage): Unplug power, data, and antenna lines from spare equipment where feasible. Turn off equipment that cannot be unplugged and is not actively being used. Use at least a lightning rated surge protection device (SPD) on power cords, antenna lines, and data cables. Wrap spare electronics with aluminum foil or put in Faraday containers.

Level 2 (Outage-Only Hours): Level 1 protection plus use EMP-rated SPDs on power cords, antenna lines, and data cables to protect critical equipment. Use on-line/double-conversion uninterruptible power supplies (UPS) or a high-quality, line interactive UPS. Use fiber-optic cables (with no metal); otherwise use shielded cables, ferrites, and SPDs. Note: shielded racks, rooms or facilities may be more cost-effective than hardening numerous cables.

Level 3 (Outage-Only Minutes): Level 2 protection plus use International Electrotechnical Commission (IEC) EMP and Intentional Electromagnetic Interference (IEMI) protection standards (IEC SC 77C series, see Appendix F, Reference 12). Shielding should be 30+ dB of protection through 10 GHz. Use EMP-shielded racks, rooms, or facilities to protect critical computers, data centers, phone switches, industrial and substation controls, and other electronics. Use “Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures” from the EMP Commission for grid cable protection planning. Use 85 V/km for E3 threshold testing. Institute IEC level hardness maintenance and surveillance (HM/HS). Level 3 allows the use of commercial standards for designing protection and performing HM/HS in a more cost-effective manner compared to Level 4.

Level 4 (Outage-Only Seconds): Level 3 protection plus use Military EMP Standards (like MIL-STD-188-125-1 (Reference 13) and MIL-HDBK-423 (Reference 14)), and 80+ dB hardening through 10

GHz. Use EMP shielding in rooms, racks, and buildings as needed to protect critical equipment. Use EMP-protected double-door entryways. Validate per Military guidelines, like Test Operations Procedure (TOP) 01-2-620 HEMP. Consider double surge protection on critical external lines entering EMP-protected areas. Institute ongoing Military Standard HM/HS programs. NPPs should consider Level 4 Protection where the EMP field strength should be attenuated by a factor of at least 99.99% by the shielding.

For the external lines coming into a building (both power and data lines), if these lines enter the building above ground, much higher voltages can be induced by E1 HEMP than inside the building, and a building-level lightning SPD should be used to avoid large voltages entering the building. A better solution is to ensure that the lines enter the building below ground as the earth will reduce the coupling to those external cables by more than a factor of 10. If this is done, then the main concern is for the coupling to the cables inside the building by fields penetrating the poorly shielded walls of typical building construction, but even this may be a minimal issue if the cable inside the building is short enough. To summarize, IEC 61000-5-10 (Reference 15) provides detailed information concerning the use of SPDs to limit the EMP voltages flowing to equipment in Levels 1 and 2 and how to set the shielding levels for a building (as recommended for Level 3 for at least 30 dB) based on the criticality of the function of the facility and the nature of the equipment inside the building. The standard also recommends simple test methods to establish the natural shielding effectiveness of an existing building, which can be used in the hardening process. The level 4 EMP protection recommendations are presented in this document for missions that cannot allow more than a few seconds of outage, and therefore require the approach provided in MIL-STD-188-125-1, which requires an 80-dB shield and the test procedures defined in the military standard.

5 EXISTING INDUSTRY STANDARDS FOR ELECTROMAGNETIC COMPATIBILITY OF NEW EQUIPMENT AGAINST COMMON ELECTROMAGNETIC THREATS AND POTENTIAL GAPS COMPARED TO AN EMP EVENT

There are potential consequences to electrical/digital equipment from each pulse component (A2473 EMP Commission Report, Reference 16). 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. The development of automated monitoring and control systems, such as SCADA systems along with their electronic cousins, DCS and PLC, have become critical elements used by the electrical utilities for applications such as generation, transmission, and distribution. In 1999, San Diego County Water Authority, Gas and Electric companies experienced severe electromagnetic interference (EMI) to their SCADA systems and associated wireless networks. The source of the EMP was not a GMD or HEMP, but determined to be radar operated on a ship 25 miles off the coast of San Diego. Although these control systems may differ from application to application and from one industry to another, typically they all share certain generic commonalities. Similar to the internals of a generic desktop personal computer (PC), these digital systems contain familiar circuit boards, chips of various sorts, and cable connectors to the external world.

Although the critical electronic elements of these systems are usually contained within some sort of metallic box, the service as a protective Faraday cage is typically minimal. They typically are not designed to protect the electronics from high-energy EMPs that may infiltrate either from the free field or from the many antennae (cable connections) that may compromise electromagnetic integrity. The major concern for vulnerability to EMP is focused only on the early-time E1 component. This is because, even in the power industry, these systems generally are not directly coupled electrically to the very long cable runs that might

be expected to couple to a late-time E3 signal. The EMP Commission sponsored and funded a series of tests of common DCS components in a government-owned EMP simulator. The simulation testing provided an opportunity to observe the interaction of the electromagnetic energy with equipment in an operational mode. The Commission consulted with experts from industry groups associated with NERC and by site and market surveys to identify representative control systems for testing. A test matrix was developed that reflected electronic control technologies employed in power generation, power distribution, pipeline distribution, and manufacturing plants. These tests included but were not limited to typical components used in an NPP such as protective relays, DCS components, PLCs, and various digital transmitters. Many of the control systems considered achieved operational connectivity through Ethernet cabling. EMP coupling of electrical transients to the cables proved to be an important vulnerability during threat illumination. A simple model of four Ethernet cables from a router to four PCs was generated to quantify the impact of cable length. The results of the analysis indicate that the coupling to the 200 feet of Ethernet line is roughly seven times the transient level on the 25-foot line measured during the test program. The testing and analysis indicate that the electronics could be expected to see roughly 100 to 700 ampere current transients on typical Ethernet cables. Effects noted in the EMP testing occurred at the lower end of this scale. The bottom-line observation at the end of the testing was that every system tested failed when exposed to the simulated EMP environment.

The failures were not identical from system to system or within a system. For example, a device with many input-output ports might exhibit degraded performance on one port, physical damage on another, and no effect on a third. Control units might report operating parameters at variance with their post-illumination reality or fail to control internal flows. Other observations ranged from electronic upset of equipment, which might be repaired by either reboot or recycle to physical damage that required the actual replacement of the affected hardware. At relatively low electromagnetic stress levels, a portion of a DCS process controller provided false indications of the process status. An operator interface indicated a switch was on when it had been turned off, while internal voltage and temperature were reported as out of their normal operating ranges when they were actually normal. Digital inputs/outputs (I/Os) have a threshold voltage where they read a field contact as “on” or “off.” With elevated EMI, this results in false readings of digital inputs when cables are not properly shielded. In addition to false readings from the sensors, direct malfunctions of some tested control elements were also noted. Additional control element effects included the failure of pressure transmitters, which included both physical damage and loss of calibration data required to indicate proper readings. The Commission considered the implications of these multiple simultaneous control system failures to be highly significant as potential contributors to a widespread system collapse. Electro-mechanical relays are immune to EMP, but electronic protective relays, although robust, are subject to upset at higher levels of simulated EMP exposure. PLCs are subject to upset and damage at moderate levels of EMP assault and some circuit boards exhibited damaging short-circuit flashover during EMP Commission-sponsored testing. General-purpose desktop computers and SCADA remote and master terminal units were the most susceptible to damage or upset of all the test articles. The RS-232 ports were found to be particularly susceptible, even at very low levels of EMP stress. Devices tested performed up to the manufacturer’s claimed levels for electromagnetic compatibility, thus, the international standards to which the manufacturers subscribe are being met. Unfortunately, the induced E1 stress is higher than the standards for normal operation.

Although some plants have turbine generators located outside, the control equipment, protective systems, sensors, and current transformers typically (but by no means always) will be inside the plant. In general, there will be no outside cable runs, so the building itself will provide some EMP protection. However, the lengths of these interior cables can be on the order of 100 meters. Cable trays may or may not provide additional protection, depending on their material and installation method. The key is not device- or component-level testing for EMP susceptibility, but overall control and protective system testing to evaluate vulnerability. Just as in the case involving power plants, the first critical issue is the proper functioning of the protective elements, specifically relays, followed by the local control systems. These elements protect the high-voltage breakers and transformers that are high-value assets. E1 is likely to disrupt

and perhaps damage protective relays, not uniformly but in statistically very significant numbers. Left unprotected, the high-value assets would likely suffer damage by the transient currents produced during the system collapse, as well as potentially from E2 and E3, depending upon relative magnitudes. Many of the effects noted in the previous paragraphs are attributed to the coupling to the wires and cables interconnecting the systems. The level of this coupling scales roughly with the length of the wire. As a general rule, the larger the transients are in the coupling lines, the more damaging they are to electronics equipment. One way to address this concern is to perform cable coupling analysis. This was done as part of the current injection test program in order to relate the susceptibility levels of electronic equipment to the EMP threat. Commission testing of some typical protective relays with lower-than-expected EMP levels provides cause for serious concern. Some of the testing methods, such as Lightning-Induced Transient (while 50 kV/m peak field is used by the IEC and military standards, some Chinese and Russian authorities have said “super-EMP” weapons can generate E1 levels as high as 100 kV/m to 200 kV/m) and Electrical Fast Transient (nearly the same as the waveshape of E1 HEMP-induced voltages), are described in the EMP Protection Guidelines (Reference 11).

6 RECOMMENDATIONS ON HOW TO MODIFY PLANT STANDARDS OR SITE EMC TEST SPECIFICATIONS TO ADDRESS AND MITIGATE EMP THREATS

More robust installation standards must be identified and implemented as appropriate; these include short shielded cables, circumferential grounding, arrestors on leads, surge protectors, and similar activities. These should include more robust system standards such as proximity to protected device, no commercial off-the-shelf (COTS) computers in mission-critical roles and similar matters. In some instances, these will qualify as add-ons and replacements during the early period initiatives. Complete the testing and evaluation work that the Commission initiated to set hardening standards for electric power protective systems.

Identify any environmental classifications that may affect immunity levels. The IEC standards provide a workflow whereby devices and systems can be evaluated for their relative immunity to HEMP. First, the component or subsystems enclosure is classified into a protection concept using IEC-61000-2-11 (Reference 17). Alternatively, the efficacy of the protective devices can be classified using IEC-61000-5-3.23 (Reference 18). After establishing these protective concepts, IEC-61000-4-25 (Reference 19) can be used to determine appropriate test levels to ensure the system or device is immune to HEMP.

IEC 61000-2-11, Classification of HEMP Environments (Commission, 1999), provides expected levels of radiative and conducted hazard for devices exposed to HEMP. This includes expected levels within various shielding concepts (e.g., various qualities of control housing in substation yards). This classification system yields a simple way of characterizing substations, and ultimately the risk to electronics such as relays within the control house. Most modern concepts reduce expected peak radiated voltages by a factor of 10 or more; however, these modern concepts may not be in general use in older facilities.

MIL-STD shielding levels are discussed in DHS reports. Some of these unclassified U.S. military standards were discussed previously, and two additional ones are mentioned here. MIL-STD-2169B (Reference 22) sets test procedures required to evaluate the effects of (HEMP) environment on military equipment and specifies both the pulse generation and measurement procedure. MIL-STD-461F (Reference 23) sets limits on the susceptibility of electrical components procured by the military to EMI and also specifies appropriate testing. These standards are not referenced or widely used in civilian applications due to the expense. Certainly, they are never completely used, although some manufactures may appeal to portions of the standard. Also, there is no gradation of scale in these standards: one either complies with the standard or not. The gradations of scale provided in the IEC standards are far more valuable.

Lastly, the Department of the Army Pamphlet No. 1110-3-2 (Reference 20) provides a comprehensive and in-depth explanation of the threat with extensive details for proper construction and installation of

components, along with shielding, grounding and other protection devices and techniques to prevent or mitigate the effects from HEMP.

7 CONCLUSIONS

As per an NEI Electromagnetic Pulse Topic Summary issued in October 2020, an EMP Task Group has been approved by the Nuclear Strategic Issues Advisory Committee (NSIAC) and established by NEI to monitor and direct the industry's response to the DOE testing plan. In response to a request from DOE/Sandia for a tour of a representative NPP for a select group to better understand the NPP structural and system designs to inform the next steps for their testing program, Dominion volunteered the North Anna Power Station to host the tour. Planning for the tour is in progress. The plant tour will allow introduction and familiarization of the beyond design basis (BDB) strategies at the station to reinforce its value for mitigation of an HEMP. Based on the results of the plant tour, support of subsequent testing and/or evaluation activities would be considered by the HEMP Task Force. Based on the above status, it is apparent that although the nuclear power industry has high confidence that the plants will be able to achieve safe shutdown and maintain the plants in this condition, there are still research and studies to be performed for each separate plant to evaluate the impact from a HEMP relative to each plant being able to return to reliable power production following such an event. Based on the above research it has been determined that a HEMP may pose a credible threat to an NPP's ability to quickly restore power to the grid. It is also apparent that the present standards used to design and install equipment in these plants may need to incorporate lessons learned from the Military Standards to develop/revise industry standards, and perform additional assessments, studies and testing for hardening of equipment to reduce vulnerabilities resulting from the threat of HEMP attacks.

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