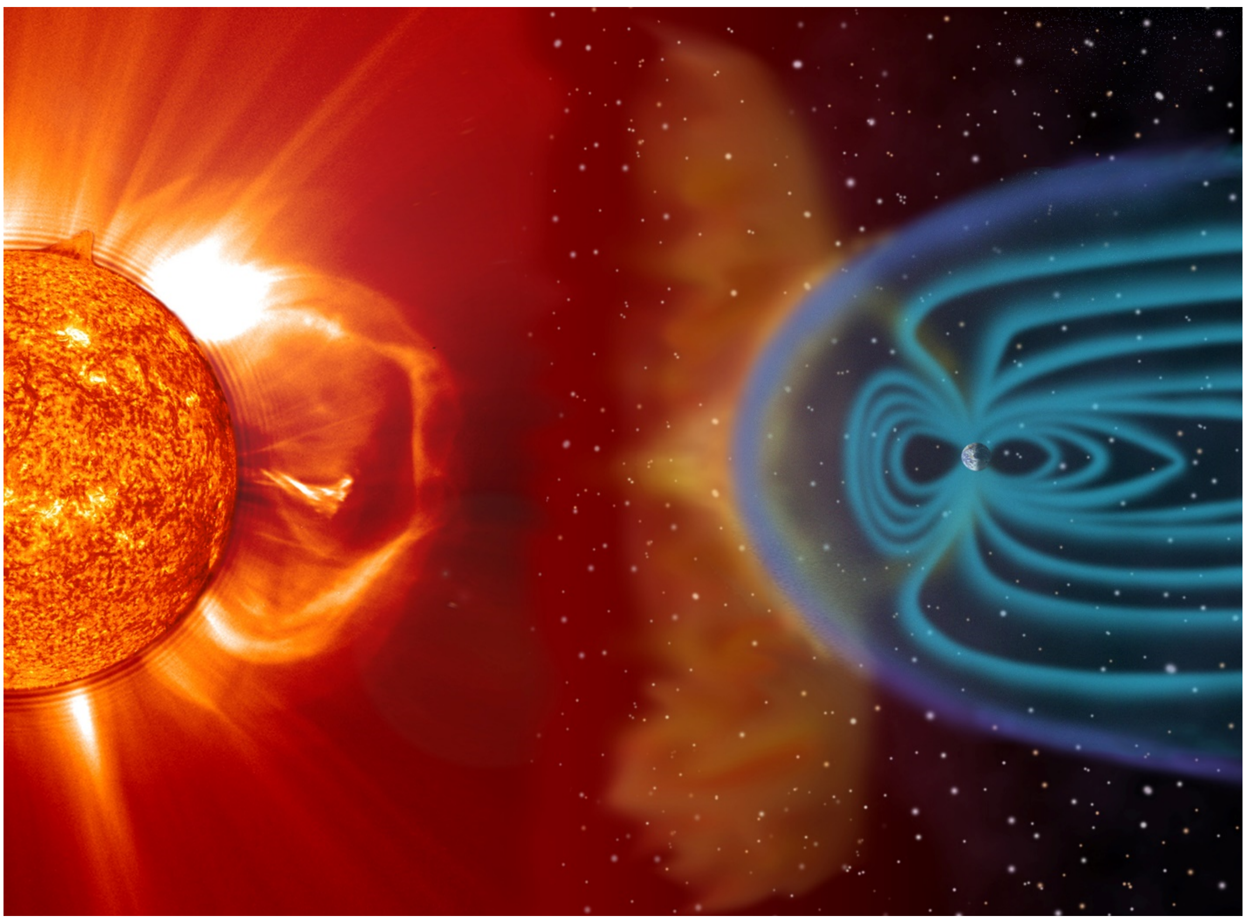
TECHNICAL LETTER REPORT

TLR-RES-DE-6

Updated Technical Review on the Ability of Operating NPPs to Safely Shutdown After an EMP Event



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Office of Nuclear Regulatory Research

Executive Summary

This report provides an update on the latest technical information regarding the ability of Nuclear Power Plants (NPPs) to safely shut down after Electromagnetic Pulse (EMP) events, including the impact of naturally occurring geomagnetic disturbances (GMD), or human-made High Altitude Electromagnetic Pulse (HEMP) E3 fields caused by a nuclear detonation, on NPP Safety Related/Important to Safety (SR/ITS) systems. The report also documents the robustness of plant equipment, existing operational procedures, the industry's Diverse and Flexible Coping Strategies – FLEX - program, and the role of manual intervention in being able to safely shutdown an NPP following EMP events.

Key findings show no direct impact of GMD or E3 fields on SR/ITS systems and other robust plant equipment. Effective existing procedures provide continued assurance of safe shutdown capabilities.

This report therefore confirms the longstanding staff technical position that NPPs will be able to safely shut down after an EMP event in light of present-day technical information; no new research alters staff's underlying assumptions or analyses. This report recommends staff continue to monitor EMP research and support United States Government (USG) interagency initiatives related to space weather. In addition to advances by NASA and others to provide real-time space weather monitoring and alerts, ongoing research continues to shed light on historic EMP events. This recommendation provides reliability in the staff's technical position while also providing openness to ongoing research and real-time monitoring of EMP events.

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Acronyms

ACE – Advanced Composition Explorer

APNSA - Assistant to the President for National Security Affairs

AU – Astronomical Unit

BDBE - Beyond-design-basis-event

CCMC - Community Coordinated Modeling Center

CME - Coronal Mass Ejection

EDG – Emergency Diesel Generator

EHV - Extreme High Voltage

EMP - Electromagnetic Pulse

EO - Executive Orders

FERC – Federal Energy Regulatory Commission

FLEX – Diverse and Flexible Coping Strategies

GDC - General Design Criteria

GIC - Ground Induced Current

GMD - Geomagnetic Disturbance

GOES - Geostationary Operational Environmental Satellites

HALEU - High Assay Low Enriched Uranium

HEMP - High-Altitude Electromagnetic Pulse

IN - Information Notice

MBDBE - Mitigation of beyond-design-basis-events

MHD - Magnetohydrodynamic

NASA - National Aeronautics and Space Administration

NERC - North American Electric Reliability Corporation

NOAA - National Oceanic and Atmospheric Administration

NPP - Nuclear Power Plant

NRC - Nuclear Regulatory Commission

NSW-SAP - National Space Weather Strategy and Action Plan

PRM - Petition for Rulemaking

SDO - Solar Dynamics Observatory

SNL - Sandia National Laboratories

SPE – Solar Proton Event

SR/ITS - Safety Related/Important to Safety

SSA - Sector-Specific Agencies

SW - Space Weather

SWAG - Space Weather Action Group

SWORM - Space Weather Operations, Research, and Mitigation

TPL-007 - Transmission System Planned Performance for Geomagnetic Disturbance Events

US – United States

USG - United States Government

USGS – United States Geological Survey

WG - Working Group

Introduction

In this report, we document the technical bases on the ability of NPPs to safely shut down after an EMP[1] event. We examine the development and research on this topic to identify changes that could impact past NRC analyses and assumptions, described in the historical research section.

In 2010, the potential impact of space weather (SW) events was considered by extrapolating previously performed HEMP analyses. The primary concern was the Geomagnetic Disturbance (GMD) caused by a Coronal Mass Ejection (CME). This GMD would in turn cause Ground Induced Currents (GICs) with the potential to directly or indirectly impact NPPs. The determination was the impact of these events would be encompassed by the prior analyses for HEMP events and thus the NPPs would be adequately protected.

In 2011, PRM 50-96. "Long-Term Cooling and Unattended Water Makeup of Spent Fuel Pools"[2] was submitted which raised the concern that an extreme SW event could overwhelm the United States (US) power grid, causing high levels of damage to the infrastructure, particularly the extreme high voltage (EHV) grid transformers – causing an extreme, up to two year, grid outage and thus a loss of offsite power to NPPs for that duration.

The focus of the PRM was specifically on the spent fuel pool, but the duration of the outage called into question whether the NPPs could maintain a safe state during this time. If sufficient concern existed, then the technical position that the plants could safely shutdown and maintain a safe state may need to be reevaluated.

After review[3] in 2012, staff determined that while there were some outstanding issues to address, the potential for a catastrophic grid collapse, and thus an event that would be beyond the plants' ability to maintain a safe state, was minimal. The staff technical position remained that the NPP fleet would be able to safely shutdown in the event of an EMP. However, further investigation would still be required to close some of the concerns raised by PRM 50-96.

Since the last NRC directed research on this topic in 2010, there have been many developments on this topic, internally to the NRC, the USG as well as externally

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[1] The term EMP is used to refer to both natural (Space Weather) and human-made (nuclear High Altitude Electromagnetic Pulse (HEMP)) in alignment with the 2019 Executive Order (EO). 13865, "Coordinating National Resilience to Electromagnetic Pulses."
[2] https://www.regulations.gov/document/NRC-2011-0069-0002
[3] ML12137A892

(publicly and internationally). This report considered these developments to determine if any could affect the staff's technical position.

Process

Consideration of Primary Factors

There are several primary factors by which the technical position is based. Taken together, these factors provide a means to evaluate whether an NPP can safely shut down after an EMP event. These factors are:

- The impact of a GMD or E3 field on SR/ITS systems
- Plant equipment required for safe shutdown
- Standard plant operating procedures
- EMP event specific plant procedures
- External considerations
    - Industry's Diverse and Flexible Coping Strategies - FLEX[4]
    - North American Electric Reliability Corporation (NERC) TPL-007[5]
- Ability of manual intervention in plant operations
    - unexpected/beyond-design-basis-event (BDBE) events

[4] NEI 12-06 "Diverse and Flexible Coping Strategies (FLEX) implementation Guide" describes the process developed by industry to enhance the capability of licensees to employ strategies to enhance their ability to cope with beyond-design-basis external events. This supports licensees compliance with 10 CFR 50.155, "Mitigation of beyond-design-basis-events (MBDBE)" – commonly referred to as the MBDBE Rule.

[5] NERC TPL-007 "Transmission System Planned Performance for Geomagnetic Disturbance Events", was developed in response to Federal Energy Regulatory Commission (FERC) Order No. 779, directing certain registered entities to assess their vulnerability to GMDs.

Analysis

The Impact of EMP on SR/ITS Systems

First, it is important to note that only safety systems are considered in this analysis. The necessary systems/functions required for the plant to shut down and maintain a safe shutdown state after an EMP are evaluated. It is also not required that these safety systems maintain full functionality after an EMP event - current regulations do not require equipment to be qualified (i.e. tested) to ensure operability after, or protected from, an EMP.

We must first consider how an EMP event could impact an NPP. There are two modes of impact. The primary mode of impact is from GICs.[6] The second mode is the high intensity, fast pulse generated by a nuclear device.[7]

The main focus in this analysis is the primary impact mode. Natural (GMD) and human-made EMP can cause GICs. For GMDs, there is a regulatory tie-in by the 10 CFR 50 GDCs to this BDBE.[8] EMP from a nuclear weapon, HEMP, is a result of a hostile actor/nation state and generally excluded from NRC consideration by 10 CFR 50.12 and 10 CFR 52.13 However, there has been historic research into HEMP EMP impacts on NPPs. In addition, existing and recent Presidential Executive Orders (EOs) necessitate some NRC engagement. Of note, the mitigation methods for natural and human-made EMP GICs are similar, so analyses performed support both types of EMP.

The main concern from GICs is voltage instability and potential grid collapse. Such a collapse will cause a loss of offsite power. The voltage issues caused by the GICs may also challenge or potentially damage plant transformers, but these transformers are not SR/ITS systems required for shutdown and thus are excluded from the discussion.[9] Occurrences such as minimal heating of generators from GICs (exhibited in some SW storms) would not present a SR/ITS system challenge. Similarly, the generally disconnected nature of such emergency assets as Emergency Diesel Generators (EDGs), as well as the lack of the extreme coupling capability for GICs as compared to the power grid[10], minimizes the risk to these systems.

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[6] Ground Induced Currents from EMP events is discussed further in the background section.
[7] Further details on the different EMP modes are provided in the background section.
[8] Regulatory considerations are addressed in more detail in the background section.
[9] Such transformers, including EHV units that are not part of the NPP but impact grid outage duration, have been found to be minimally susceptible to damage.
[10] The lack of a long line conductor similar to that presented by the power grid reduces the ability of the energy from these events to couple into the EDG.

Thus, the credible concern from the primary mode EMP is the impact of an extended loss of offsite power. There are no other identified significant means of potential damage to the SR/ITS systems from the primary mode EMP.

For the secondary mode, the impact is a result of the high intensity, fast pulse from a HEMP[11]. This pulse can damage or destroy unprotected electronic equipment. Safety systems may experience some functional degradation; however, the robustness of plant procedures and the capability for manual operator intervention, provides assurance that NPPs will be able to safely shutdown after a HEMP EMP. Additionally, a 2019 EPRI[12] study, "High-Altitude Electromagnetic Pulse Effects on Bulk-Power Systems: An Overview" indicates a high level of survivability of electrical and digital control systems when exposed to these pulses.

[11] This is more precisely referred to as the E1 field or waveform. This is discussed further in the background section.
[12] Not publicly available.

Review of Technical Bases

This review had a dual purpose. First, it considered the state of knowledge as of the last NRC directed research in 2010, which supported the technical stance that an NPP could safely shut down after an EMP event. Second, it sought to identify any changes in knowledge since 2010 that negatively affect the evaluation of relevant factors, potentially necessitating a reassessment of the staff's technical position.

To assess the staff's technical stance, we conducted an initial review of research and information available since 2010, focusing exclusively on potential impacts to NPPs. For instance, while developments might have changed the understanding of damage to the power grid from an EMP event, the primary concern was the long-term loss of offsite power. We treated any positive development, such as a reduced expectation of power grid outage, as a net zero change in our analysis to maintain conservatism in the results. Conversely, we further examined any negative development (increased potential for adverse impact) to determine if recent positive developments could offset it. This approach aimed to ensure conservative results.[13]

The review identified several common themes, notably the focus on the overall impacts of EMP events on critical infrastructure. Given that NPPs are part of the nation's critical infrastructure, we concentrated on potential specific impacts that could impact NPPs.

Regarding EMP-generated GICs, the primary concern remained the long-term loss of offsite power due to impacts on the power grid. We identified no new credible modes of adverse impact to NPPs from GICs.

There were new developments, such as research questioning the adequacy of the current baseline for natural EMP events[14] and additional evaluations of the possible impact to the grid. However, these developments did not provide new information that challenged the staff's technical position.

Another key concern was the HEMP high intensity, fast pulse, or E1 field. Analysis and published waveform data[15] did not reveal significant changes in the potential impact on plant systems that could affect safe shutdown capabilities. This determination was based on three points:

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[13] Due to the lack of substantial statistical information on extreme EMP events, combined with the minimal NPP testing performed for the BDBE, a more subjective approach was used.
[14] As NERC TPL-007 is updated, changes to the baseline event have been discussed. Additional historical information on events such as Miyake Events has been identified.
[15] United States Department of Energy, "DOE Memorandum: Physical Characteristics of HEMP Waveform Benchmarks for Use in Assessing Susceptibilities of the power Grid, Electrical Infrastructures, and other Critical Infrastructure to HEMP Insults," January 2021.

- The original rationale for the staff's technical position,
- The factors that mitigate potential failure impacts from such events,
- The lack of a requirement for all plant systems to remain functional post-event.

General research on hardware susceptibility to an E1 field was relevant only at a component level. The focus of system testing research was primarily on survivability and performance during and after an event. No comprehensive system tests were found that provided actionable results for an NPP-wide application. As previously stated, NPPs do not require full system functionality in these scenarios.

Given the limitations in available, pertinent information, this effort had to consider the impact of E1 on plant systems as was previously done. No information was discovered that definitively invalidated any underlying assumptions of past technical evaluations. Therefore, regarding the impact of the E1 field, the technical position remains valid.

The following is an brief summary of the applied process for one comparison.

> *In evaluating the staff's technical position on the impact of EMP events on NPPs, we considered recent developments in grid reliability and transformer resilience. A key positive development has been the understanding of design improvements to EHV transformers, making them less susceptible to EMP-related damage. This improvement significantly improves the grid's expected resilience to EMP events, potentially reducing the likelihood of long-term loss of offsite power to NPPs.*
>
> *This positive development was then considered along with a negative finding: historical evidence suggests the occurrence of solar events more intense than the Carrington Event, known as Miyake Events. Such evidence points to the potential for more extreme EMP events than previously accounted for in grid and NPP resilience planning.*
>
> *Despite the negative implications of potentially stronger EMP events, the positive development of more resilient EHV transformer designs plays a crucial role in mitigating these concerns. The improved resilience of the grid infrastructure means that, even in the face of a more intense EMP event, the likelihood of a long-term loss of offsite power does not increase. This is because the existing grid, with the less susceptible transformer designs, is expected to collapse due to instability, rather than from direct damage by the EMP itself. Thus, the more resilient design of EHV transformers offsets the increased risk posed by the potential for significantly greater EMP events. And as the grid is expected to collapse prior to damage, the duration of a loss of offsite power is not expected to increase.*

In summary, while the evidence of more intense historical EMP events introduces a new challenge to grid and NPP resilience planning, the reduced susceptibility of EHV transformers is a significant counterbalance. This understanding supports maintaining the staff's technical position that an NPP can safely shut down in the event of an EMP. This evaluation demonstrates that the positive developments in grid resiliency effectively offset any increased risk from potentially stronger EMP events, affirming the validity of the staff's technical position on NPP safety in the face of EMP threats.

Findings and Recommendations

Based on this review, we find that the technical bases for the staff's position on EMP events has not significantly changed.

The NRC continues to monitor technical developments in the field of EMP research and potential protections/mitigations. The NRC will stay informed of the latest national and international research and will work with USG agencies, industry partners, and the international community to maintain a comprehensive understanding of the risks posed by EMP events and identify best practices to address them.

While the agency supports and will continue to engage in USG and other external efforts to evaluate and prepare to manage and mitigate the infrastructure impacts of an EMP event, these are implementation and forward-thinking efforts, and do not impact the underlying technical considerations. However, any technical changes resulting from such efforts will be monitored and, as appropriate, evaluated to determine if any potential impact on the staff's technical position is created.

Background

The following material provides additional background and supplemental information on EMP. It is intended to be a very brief introduction to several topics of interest in the area. These topics are of use when considering the overall issue of EMP and the potential impact to NPPs.

Regulatory Considerations

To address the specific regulatory context for the NRC regarding hostile actions and EMP, we focus on the relevant sections of 10 CFR 52.10, 10 CFR 50.13 as well as the General Design Criterion (GDC) in 10 CFR 50. While 10 CFR 52.10 and 50.13 set clear boundaries on NRC's role in matters related to hostile actions, the GDC under 10 CFR 50 provide a framework for addressing the impacts of natural GMD on NPPs.

Hostile Actions – 10 CFR 52.10 and 50.13

NRC does not require NPP licensees to protect against a HEMP. Regulations under 10 CFR 52.10 and 10 CFR 50.13 provide guidance on NRC's limitations in requiring actions from licensees to protect against attacks and destructive acts by enemies of the US. Notably, these regulations delineate the boundary of NRC's authority, acknowledging that certain security measures fall outside the scope of nuclear safety and are instead under the purview of national defense and security agencies.

Space Weather Impacts – General Design Criteria in 10 CFR 50

The NRC does require that licensees have the ability to safely shutdown the reactor in response to scenarios that include the loss of off-site power to the plant. GMD is a natural phenomenon which can result in such an event. The GDC in 10 CFR 50, provide guidance on how the NRC considers these phenomena.

- *10 CFR Part 50, Appendix A, GDC 2, "Design bases for protection against natural phenomena,"* requires that structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions.
- *10 CFR Part 50, Appendix A, GDC 17, "Electric Power Systems,"* requires, in part, that nuclear power plants have onsite and offsite electric power systems to permit the functioning of structures, systems, and components that are important to safety.
- 1*0 CFR Part 50.63, "Loss of All Alternating Current Power,"* requires that each light-water-cooled nuclear power plant be able to withstand and recover from a station blackout (i.e., loss of the offsite electric power system concurrent with reactor trip and unavailability of the onsite emergency ac electric power system) of a specified duration.

In addition*, Information Notice (IN) 90-42, "Failure of Electrical Power Equipment Due to Solar Magnetic Disturbances,"* was issued following the March 13, 1989 geomagnetic storm that caused major damage to electrical power equipment in Canada, Scandinavia, and the United States. The intent of the IN was to alert the nuclear plant owners about possible failure modes of electrical power equipment in NPPs and the connected transmission systems due to solar magnetic disturbances. The events described in the IN were considered as precursors to station blackout or partial loss of offsite power.

MBDBE Rule

10 CFR 50.155, "Mitigation of beyond-design-basis-events" – commonly referred to as the MBDBE Rule - is a regulatory requirement established in response to the Fukushima Daiichi nuclear accident. The rule requires NPPs to maintain strategies for mitigating beyond-design-basis events, which are events that are not considered in the design of the plant due to their low probability. EMP events fall into this category.

The MBDBE Rule requires plants to have resources and procedures in place to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities following a beyond-design-basis event. This includes the use of portable and installed equipment, as well as strategies for managing the loss of large areas of the plant due to explosions or fires.

Executive Orders

The 2016 EO 13744, "Coordinating Efforts to Prepare the Nation for Space Weather Events," initiated a comprehensive effort to prepare for and mitigate SW impact to critical infrastructure such as electrical power, water supply, healthcare, and transportation. This EO was the culmination of a six-year focus on SW within the White House and built upon the National Space Weather Strategy and National Space Weather Action Plan released in 2015.

The EO outlines specific roles and responsibilities for various federal agencies:

- The Department of Defense is tasked with providing operational SW observations and forecasts to support its missions and defense.
- The Department of the Interior supports research and development related to Earth's magnetic field and solar-terrestrial interactions.
- The Department of Commerce, through National Oceanic and Atmospheric Administration (NOAA), provides operational SW forecasts, warnings, and real-time monitoring for various sectors.

- The Department of Energy is responsible for protecting and restoring the reliability of the electrical power grid during space weather-related emergencies.
- The Department of Homeland Security ensures the redistribution of SW alerts and coordinates response and recovery efforts for critical infrastructure.
- National Aeronautics and Space Administration (NASA) focuses on research programs to understand solar interactions with Earth, develops space-weather-related missions, and aids in transitioning SW models from research to operations.
- The National Science Foundation supports fundamental research linked to societal needs for SW information.
- The Secretary of State is involved in diplomatic efforts to strengthen global capacity to respond to SW events.

Additionally, the EO mandates the development of a national policy for SW and the establishment of an interagency coordination body within the National Science and Technology Council to implement this policy. It also emphasizes the need for collaboration across governments, emergency management communities, academia, media, insurance industry, non-profits, and the private sector for comprehensive preparedness.

The 2019 EO 13865, "Coordinating National Resilience to Electromagnetic Pulses," continues enhancing the national preparatory posture by addressing both natural and human-made EMP threats. This EO emphasizes the importance of preparedness and resilience against EMP events, which can disrupt, degrade, and damage critical technology and infrastructure systems.

Key aspects of this EO include:

- Intelligence and Risk Assessment: The EO tasks the Assistant to the President for National Security Affairs (APNSA) with coordinating the development and implementation of actions to assess and manage the risks of EMPs. This includes collecting, analyzing, and disseminating intelligence-based assessments on adversaries' capabilities and the likelihood of EMP attacks.
- Enhancing Information Sharing: The EO directs the heads of Sector-Specific Agencies (SSAs), in coordination with the Department of Homeland Security, to improve information sharing with the private sector. This collaboration is vital for identifying vulnerabilities and enhancing preparedness for EMP effects.
- All-Hazards Preparedness Planning: Agencies supporting National Essential Functions are instructed to ensure their all-hazards preparedness planning adequately addresses EMPs, including through mitigation, response, and recovery measures.

- Identifying Critical Functions and Infrastructure: The Department of Homeland Security, in coordination with SSAs, is responsible for identifying national critical functions and associated priority critical infrastructure at greatest risk from EMP disruptions. This includes assessing which infrastructure systems, networks, and assets are most vulnerable to EMP effects.
- Improving Understanding of EMP Effects: The EO mandates a focus on understanding the effects of EMPs. This includes assessments of vulnerable critical infrastructure and developing standards and mitigation strategies.
- Focus on Both Natural and Human-made EMPs: The EO recognizes the threat from both natural EMP events, such as extreme geomagnetic disturbances (GMDs) caused by solar activity, and human-made EMPs, including high-altitude nuclear detonations and specialized conventional munitions.

The EO represents a comprehensive approach to enhancing national resilience to EMP threats, acknowledging the potentially catastrophic impact of EMPs on public health, safety, economic security, and national security. It underlines the need for a coordinated effort involving various government agencies and private sector partners to address these complex and significant challenges.

FLEX

Industry developed the Diverse and Flexible Coping Strategies – FLEX – program in response to the needs identified by the Fukushima Daiichi accident in Japan in 2011. This event highlighted the need for enhanced safety measures and backup systems to address extreme events that might lead to a loss of power and cooling capabilities at NPPs. FLEX is part of a comprehensive strategy to improve the safety and resilience of NPPs against such scenarios. Here are the key aspects of the FLEX capability:

- Enhanced Safety Measures: FLEX involves the deployment of portable, backup safety equipment that can be used in the event of a severe accident or a natural disaster that causes the loss of power and cooling capabilities. This includes additional pumps, generators, batteries, and other equipment that can be quickly mobilized to ensure the continued safe operation of the plant.
- Diverse and Flexible Response: The core idea behind FLEX is to have a diverse and flexible response capability. Instead of relying on fixed, single-purpose safety systems, FLEX allows for a more adaptable approach using a range of equipment that can be deployed on an as needed based on the specific circumstances of the emergency.
- Regional Support Centers: To support the FLEX program, regional response centers have been established. These centers stockpile necessary equipment and can quickly deploy it to a nuclear site in need. This ensures that even if a plant’s onsite

equipment is damaged or inaccessible, additional resources can be brought in from these regional centers.

- Enhanced Training and Drills: The implementation of FLEX includes comprehensive training for plant personnel in the use of portable equipment and in the procedures for responding to a wide range of emergency scenarios. Regular drills and exercises are conducted to ensure readiness.
- Regulatory Compliance: the NRC has incorporated aspects of the FLEX strategy into its regulatory requirements for NPPs. This ensures a standardized approach to emergency preparedness across the industry.
- Global Influence: The FLEX program has influenced nuclear safety strategies worldwide. Many countries with nuclear power capabilities have looked to the FLEX approach as a model for enhancing their own safety measures.
- Continuous Improvement: The FLEX program is not static; it is subject to ongoing evaluation and improvement. As new technologies and strategies for emergency response are developed, they can be integrated into the FLEX framework.

NEI 12-06 "Diverse and Flexible Coping Strategies (FLEX) implementation Guide" describes this program in more detail. FLEX supports licensees compliance with 10 CFR 50.155, "Mitigation of beyond-design-basis-events" – the MBDBE Rule.

NERC TPL-007 Reliability Standards

In May 2013, the Federal Energy Regulatory Commission (FERC) issued Order 779 which directs NERC to submit reliability standards that address the impact of GMD on the reliable operation of the Bulk-Power System.

As a result, NERC TPL-007, "Transmission System Planned Performance for Geomagnetic Disturbance (GMD) Events" was developed. It has undergone several revisions to enhance the reliability and resilience of the Bulk-Power System against geomagnetic disturbances.

- TPL-007-1: This initial version of the standard focused on requiring entities to assess the impact on their systems from a defined event, known as the "Benchmark GMD Event." This laid the foundation for a systematic approach to understanding and mitigating the risks posed by GMDs to the power grid.
- TPL-007-2: The second version introduced new requirements (R8, R9, and R10) for responsible entities to assess the potential implications of a "Supplemental GMD Event" on their equipment and systems. This version responded to the directives in FERC Order No. 830, expanding the scope of the assessment to consider additional geomagnetic disturbance scenarios.
- TPL-007-3: The third iteration of the standard incorporated a Canadian variance, allowing Canadian Registered Entities to leverage their specific operating experiences, observed GMD effects, and ongoing research. This variance was

designed to define alternative Benchmark and Supplemental GMD Events that reflect the unique geographical and geological characteristics of Canada.

- TPL-007-4: The latest version, TPL-007-4, mandates owners and operators of the Bulk-Power System to conduct initial and ongoing vulnerability assessments of the potential impact of defined geomagnetic disturbance events on both equipment and the system as a whole. This version addresses FERC Order No. 851 related to requirements for corrective action plans. Specifically, it requires the development and implementation of corrective action plans to mitigate vulnerabilities assessed from supplemental GMD events and revises the process for time extensions in implementing these plans, favoring a case-by-case approach.

Version	Implementation Date	Superseded
TPL-007-1	November 2016	Superseded by TPL-007-2
TPL-007-2	October 2017	Superseded by TPL-007-3
TPL-007-3	November 2019	Superseded by TPL-007-4
TPL-007-4	October 2020	Current

National Space Weather Strategy and Action Plan (NSW-SAP)

The NSW-SAP was published in March 2019. It was developed by the SWORM subcommittee with public input through Federal Register 83 FR 17526, the National Security Council, and the National Space Council. The NSW-SAP identified actions to enhance the United States' preparedness for SW events for the following five years.

The main objectives of the plan are threefold:

- Enhancing the protection of critical infrastructure and national security assets. This involves safeguarding essential systems and networks from the potential disruptions caused by SW events.
- Improving the accuracy and timeliness of space weather forecasts. By advancing forecasting capabilities, the plan aims to provide more reliable and prompt information, which is crucial for effective decision-making and mitigation strategies.
- Establishing procedures for responding to and recovering from SW events. This includes developing comprehensive response plans to ensure quick and efficient recovery from any disruptions caused by SW.

Additionally, the plan recognizes the need for collaboration across various sectors, including federal agencies, academia, and private industry, to effectively address the challenges posed by SW. This collaborative approach is aimed at enhancing the nation's overall capacity to predict, prepare for, and respond to SW events.

As of January 2024, a revision to the plan is underway.

Basics of Electromagnetic Pulse (EMP)

Definition and Explanation of Electromagnetic Pulse

An EMP is a burst of electromagnetic radiation that can result from various sources such as a sudden discharge of electricity, geomagnetic storms triggered by CMEs, a lightning strike, or a nuclear explosion. EMPs can have a wide range of frequencies and energy levels. Depending on their intensity and the environment in which they occur, EMPs can have significant effects on electronic equipment and electrical systems.

One source of human-made EMPs is a high-altitude nuclear explosion or HEMP. When a nuclear weapon is detonated at high altitudes (approximately 25 miles (40 kilometers) or greater above the earth's surface) gamma rays are released that interact with air molecules in the Earth's atmosphere. This interaction generates a powerful electromagnetic field that can induce high currents in electrical systems and electronic devices, potentially causing widespread damage and disruption. After this initial pulse of high-energy, a subsequent field couples additional energy into the ground causing an additional impact. Generally, these events have a rapid onset and are expected to be relatively localized in coverage with durations in minutes.

EMPs can also be naturally occurring, such as the electromagnetic energy released during a lightning strike or a geomagnetic storm caused by solar activity. These natural EMPs tend to be less intense than those caused by nuclear explosions but can still have significant effects on electrical systems as a result of the ground currents they induce. These events are slow onset and can cover a large segment of the Earth with duration potentially lasting hours to days.

Space Weather and GMDs

Space weather refers to the varying environmental conditions in space as influenced by the Sun and the solar wind. It encompasses a range of phenomena including solar flares, CMEs, solar energetic particles, and variations in the solar wind and the Earth's magnetic field. These phenomena can interact with the Earth's magnetosphere, ionosphere, and atmosphere, affecting both space-based and ground-based technological systems.

Solar flares are sudden and intense bursts of radiation and energy from the surface of the Sun. CMEs are massive bursts of solar wind and magnetic fields rising above the solar corona or being released into space. These CMEs may be Earth directed, and upon arrival, can cause GMDs. GMDs are disturbances in the Earth's magnetic field caused by these solar phenomena. These disturbances can induce currents (GICs) that flow through power lines, pipelines, and the Earth's surface.

Types of HEMP Waveforms (E1, E2, E3)

For the human-made HEMP event, there are three distinct types of waveforms, referred to as E1, E2, and E3, each with different characteristics and effects:

- E1: This is a very fast component of a nuclear EMP. It is a brief but intense electromagnetic field that can induce very high voltages in electrical equipment. E1 can damage electronic equipment and is too fast for ordinary surge protectors to provide effective protection against.
- E2: This component is somewhat similar to the electrical pulses produced by lightning. E2 lasts a bit longer than E1 but is less intense. Most infrastructure is generally protected against lightning strikes, and the protections against lightning are also effective against E2.
- E3: This is a slow pulse, lasting tens to hundreds of seconds. It is caused by the nuclear detonation's temporary distortion of the Earth's magnetic field. E3 can induce currents in long electrical conductors, potentially damaging components such as power line transformers. This component of the HEMP waveform is similar to a SW GMD.

Comparison of SW GMD and HEMP

SW GMD and HEMP are two distinct EMP phenomena that both involve electromagnetic disturbances, but they originate from different sources and have different characteristics and impacts.

Both GMD and HEMP can cause disruptions to the Earth's electromagnetic environment, which can have significant effects on electrical and electronic systems. They can induce currents in electrical conductors, potentially causing damage to power grids, communication networks, and electronic devices.

A significant difference between GMD and HEMP is their origins. HEMPs are associated with human-made nuclear detonations. On the other hand, GMD is a natural phenomenon associated with CMEs.

The characteristics and impacts of GMD and HEMP also differ. HEMPs are typically characterized by a rapid, intense burst of electromagnetic energy, which can cause immediate and severe damage to electronic systems, with a following energy wave which couples energy into the ground. GMDs, on the other hand, involve slower, more prolonged disturbances to the Earth's electromagnetic environment. While GMDs can still cause significant disruptions, the effects are typically less immediate and can be more readily mitigated with proper forecasting and preparation.

Combined Term: EMP Events

Given the similarities between GMD and HEMP, it is useful to consider them together under the combined umbrella of EMP. This term encompasses both human-made HEMP events and natural GMD events, recognizing that both types of events can pose significant risks.

The use of the combined term EMP reflects a growing understanding of the interconnectedness of these risks. For instance, the EO 13865, “Coordinating National Resilience to Electromagnetic Pulses”, issued by the US government in 2019, collectively addresses both GMD and HEMP. The order recognizes that both types of events can have "significant effects on critical infrastructure" and calls for increased coordination and planning to enhance national resilience to EMP events.

Solar Cycles and Their Impacts

The Sun goes through an approximately 11-year cycle known as the solar cycle. During this cycle, the Sun's magnetic field goes through a periodic change, which is manifested through varying numbers of sunspots, solar flares, and CMEs. The solar cycle has a significant impact on SW and, consequently, on Earth.

During the solar maximum, the Sun has the highest number of sunspots, and the frequency of solar flares and CMEs is higher. This leads to an increased likelihood of geomagnetic storms on Earth. During the solar minimum, the Sun is relatively quiet, with fewer sunspots and less solar activity.

We are currently in the rising phase of Solar Cycle 25. This cycle began with the solar minimum in December 2019 and the solar maximum is expected approximately July 2025. The official dates of these cycle milestones are not defined by time, but by solar activity. Therefore, it may take months to actually determine they have occurred.[16]

Extreme SW events can occur at any time during a solar cycle. While the greater solar instability during a solar maximum increases the potential for such an event, it is not a prerequisite for an extreme CME or other SW activity.

[16] https://www.nasa.gov/news-release/solar-cycle-25-is-here-nasa-noaa-scientists-explain-what-that-means/#:~:text=December%202019%20marks%20the%20beginning%20of%20Solar%20Cycle,ramp%20up%20until%20solar%20maximum%2C%20predicted%20for%202025.

Historical Events

Significant Space Weather Events

There have been several significant SW events in the technological age[17] that had notable impacts on Earth. Two of the more famous are the Carrington Event of 1859 and the Halloween Storm of 2003.

- Carrington Event (1859) [18]: The Carrington Event is the most powerful geomagnetic storm recorded during the technological age. It was caused by multiple CMEs impacting the magnetosphere. The event caused widespread issues for the telegraph systems, which were the primary means of communication at that time. Operators experienced electric shocks, and telegraph pylons threw sparks. The auroras caused by the event were so bright that people in the northeastern United States could read newspapers by their light.
- Halloween Storm (2003) [19]: In late October and early November 2003, a series of solar flares and CMEs hit Earth, causing geomagnetic storms. These storms caused satellite malfunctions, power outages, and the rerouting of polar flights to avoid communication blackouts and increased radiation.

Some other events include the March 1940 Superstorm[20] and May 1921 storm[21].

Limits on Historical SW GMD Events

The historical record for SW GMD events is limited; however, GMD research is also informed by the study of nuclear detonations and associated EMP effects. For example, the 1962 Starfish Prime nuclear test provides relevant information. In addition, information on ancient EMP events (Miyake Events) is becoming available by proxy (ice cores, tree rings) allowing researchers to learn from these EMP events predating the technological age.

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[17] The technology did not exist to monitor space weather storms prior to the mid-1800s. Such events occurred but must be evaluated based on minimal historical records such as auroras. Additionally, some events left markers in ice cores or tree ring data. This topic is discussed further in the Miyake Events section of the background.

[18] Tsurutani, B. T., W. D. Gonzalez, G. S. Lakhina, and S. Alex (2003), The extreme magnetic storm of 1–2 September 1859, *J. Geophys. Res.*, 108, 1268, doi:10.1029/2002JA009504, A7.

[19] A Carrington-like geomagnetic storm observed in the 21st century, Consuelo Cid, Elena Saiz, Antonio Guerrero, Judith Palacios, Yolanda Cerrato J. Space Weather Space Clim. 5 A16 (2015) DOI: 10.1051/swsc/2015017

[20] Jeffrey J. Love; E. Joshua Rigler; Michael D. Hartinger; Greg M. Lucas; Anna Kelbert; Paul A. Bedrosian (2023) "The March 1940 Superstorm: Geoelectromagnetic Hazards and Impacts on American Communication and Power Systems" doi:10.1029/2022SW003379.

[21] Phillips, Tony (12 May 2020).”The Great Geomagnetic Storm of May 1921.”

HEMP Events (e.g., Starfish Prime Nuclear Test)

One of the most notable historical nuclear EMP events was the Starfish Prime nuclear test conducted by the United States on July 9, 1962. The test involved the detonation of a nuclear weapon at an altitude of approximately 250 miles (400 kilometers) above the Pacific Ocean. The explosion was expected to be contained in space, but it unexpectedly resulted in a pulse that caused electrical damage approximately 900 miles (1500 kilometers) away in Hawaii. Streetlights were blown out, alarms were triggered, and communication equipment was damaged.[22]

Another significant event was the Soviet Test 184 in 1962, [23]which was similar to the Starfish Prime test. It resulted in a pulse over Kazakhstan, damaging the electrical grid.

Miyake Event and Super Storm Events

Miyake events refer to sudden and extreme spikes in radiocarbon (Carbon-14) levels found in tree rings, which are indicative of significant increases in cosmic ray activity impacting the Earth. These events are named after Japanese scientist Fusa Miyake, who first identified such an event in 2012. The initial discovery pertained to a rapid increase in Carbon-14 content in tree rings dated to 774-775 AD, pointing towards a massive burst of cosmic radiation, significantly stronger than typical solar activity or any recorded SW phenomena.

Subsequent research has identified similar events, notably around 994 AD and several others scattered through the past 10,000 years. These events are characterized by their relative strength, with the intensity of the radiation spike being a key differentiator from standard solar cycles or even known solar storms such as the Carrington Event of 1859.

Proxy evidence of these events, including changes in Carbon-14 and Beryllium-10 isotopes, is primarily found in dendrochronologically dated tree rings and ice cores. The increase in Carbon-14 is attributed to enhanced cosmic ray flux, which converts atmospheric nitrogen into Carbon-14. Similarly, Beryllium-10 levels increase due to spallation reactions caused by cosmic rays impacting the Earth's atmosphere. These isotopes serve as indirect measurements of past solar and cosmic ray activity, providing insights into historical SW events that occurred before the technological age.

The attribution of these radiocarbon spikes to SW phenomena, particularly solar proton events (SPEs) or CMEs, is supported by the scale and rapid onset of the observed Carbon-14 increases. Research suggests that only a highly energetic solar event could generate such widespread and synchronized radiocarbon enhancements across both hemispheres.

[22] http://ece-research.unm.edu/summa/notes/SDAN/0031.pdf
[23] https://nuclearweaponarchive.org/News/Loborev.txt

In terms of relative strength, Miyake events are believed to be much stronger than any solar storm recorded in the technological age, including the Carrington Event. However, such an event does not necessarily imply a greater risk to the NPPs since the grid collapse will still occur due to instability and thus below the damage threshold. The resulting loss of offsite power remains the event of concern to NPPs.

Ground Conductivity

Role of Ground Conductivity in EMP Events

Ground conductivity plays a significant role in determining the effects of EMP on the Earth's surface. When a geomagnetic storm occurs, the intensity and distribution of the resulting GICs are highly dependent on the conductivity of the ground.

In regions with high ground conductivity, GICs can be more intense, leading to a higher risk of instability and potential damage to electrical infrastructure such as power grids. Conversely, in areas with low ground conductivity, the induced currents are weaker. The US Geological Survey (USGS) and other organizations are actively researching ground conductivity to better understand its role in EMP events.

Impact of Proximity to Water Bodies

The proximity to water bodies significantly influences ground conductivity. Water, especially saltwater, is a good conductor of electricity. Consequently, regions near oceans, seas, or other large bodies of water tend to have higher ground conductivity. This means that coastal areas and regions near large lakes or rivers have greater susceptibility to the effects of EMP events. GICs in these areas can be more intense, posing a higher risk to the power grid, communication networks, and other critical infrastructure.

Three-dimensional Ground Conductivity Mapping

Three-dimensional ground conductivity mapping is an advanced technique used to create detailed models of the variations in ground conductivity across different geographic regions. This technique involves the use of geophysical surveys and measurements to map the electrical properties of the Earth's crust in three dimensions.

One of the key organizations involved in three-dimensional ground conductivity mapping is the USGS. The USGS has been working on the development of three-dimensional geophysical models that can be used to assess the geoelectric hazards associated with geomagnetic storms.

Current plans are to complete the US three-dimensional mapping in 2025. There is a goal to expand this mapping to regions of Canada.

Hazard Maps Versus Scenario Maps

Understanding Hazard Maps

Hazard maps are tools used by scientists, planners, and decision-makers to visualize and understand the potential risks posed by natural and human-made hazards. These maps depict areas that are susceptible to a particular hazard based on historical data, scientific models, and other relevant information. The hazard could be anything from earthquakes and floods to SW events.

For instance, a hazard map for SW might depict areas that are at high risk of experiencing severe impacts from geomagnetic storms based on factors such as ground conductivity and proximity to the magnetic poles. These maps can be used to guide the placement and design of infrastructure, develop emergency response plans, and inform public safety measures.

Hazard maps for solar storms are being developed by organizations including the USGS and NOAA. These maps will use data from historical solar storms and geophysical models to identify areas that are at high risk of experiencing GICs and other effects of solar storms.

Understanding Scenario Maps

Scenario maps, on the other hand, are used to visualize the potential impacts of a specific event or scenario. These maps are based on detailed simulations of a particular event, considering various factors such as the intensity of the event, local conditions, and the vulnerability of infrastructure.

For instance, a scenario map for a solar storm might depict the potential impacts today of an extreme geomagnetic storm similar to the 1859 Carrington Event. This could include areas that are likely to experience power outages, communication disruptions, and other effects. Scenario maps can be used for planning and preparedness exercises, risk assessments, and decision-making.

Scenario maps for solar storms are being developed by various organizations and researchers. These maps will use sophisticated models to simulate the effects of extreme solar storms, providing insights into the potential impacts and vulnerabilities.

Comparison with Flood and Earthquake Maps

Hazard and scenario maps for SW are similar in concept to those used for floods and earthquakes. They all aim to visualize the potential risks and impacts of natural hazards, guiding planning, preparedness, and decision-making.

However, there are also some key differences. Flood and earthquake maps are often based on more extensive historical data and have been refined over a longer period. They also typically consider more local factors, such as topography and soil conditions.

In contrast, hazard and scenario maps for SW are a relatively new field. They rely more heavily on scientific models due to the limited historical data on extreme solar storms. They also have to consider global factors, such as the Earth's magnetic field and ground conductivity, which can vary widely across different regions.

Past NRC EMP Research

The NRC has recognized the importance of EMP for many years. Research on the direct and indirect susceptibility of SR/ITS systems, as well as other non-safety systems, and security-related systems to EMP, is important to the agency. Notably, the NRC worked with Sandia National Laboratories (SNL) to evaluate the effects of EMP on NPPs in studies published in 1983, 2009, and 2010.

In the late 1970s, concerns with EMP-induced large currents and voltages in electrical systems led the NRC to undertake research to study the effects of nuclear EMP on nuclear power plant safe shutdown systems. The NRC results are documented in NUREG/CR-3069, "Interaction of Electromagnetic Pulse with Commercial Nuclear Power Plant Systems,"[24] issued in February 1983. The study concluded that the safe shutdown capability of NPPs would survive the postulated human-made EMP event.

In the 2007 to 2009 timeframe, NRC staff updated NUREG/CR-3069, recognizing that the modernization of nuclear plants with digital systems, could potentially make them more susceptible to EMP. The updated study, entitled "Assessing Vulnerabilities of Present Day Digital Systems to Electromagnetic (EM) Threats at Nuclear Power Plants," [25] was published in 2009 Further, a supplemental study, completed in 2010, analyzed and compared at a high level the potential impacts on NPPs from SW events to those of the EMP events previously analyzed and reached a similar conclusion. This report is entitled "A Comparison of HEMP MHD and Geomagnetic Induced Currents and a Preliminary Assessment of Digital System Vulnerability at Nuclear Power Plants," [26]. Both of the reports concluded that NPPs could achieve safe shutdown following an EMP event.

In 2008, the Congressionally chartered EMP Commission[27] published the "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse

[24] http://prod.sandia.gov/techlib/accesscontrol.cgi/1982/822738-2.pdf
[25] ADAMS Accession Number ML111670006 – not publicly available
[26] ADAMS Accession Number ML111670005 – not publicly available
[27] http://www.empcommission.org/

(EMP) Attack."[28] In support of EO directed activities, the EMP Commission report was subsequently reviewed in conjunction with the NRC directed EMP analyses. Corresponding parameters and criteria from the report applicable to the NRC regulatory environment were examined against these studies and validated the technical position that NPPs can safely shutdown after an EMP event.

Space Weather Action Group (SWAG) and Space Weather Operations, Research, and Mitigation (SWORM)

The SWAG and the SWORM are two USG interagency initiatives related to space weather management, mitigation, and research.

SWAG primarily focuses on the coordination and enhancement of space weather services. It involves various stakeholders, including government agencies and international bodies, working together to improve SW forecasting, monitoring, and impact assessment.

SWORM, on the other hand, plays a more comprehensive role. It is dedicated to addressing the challenges posed by SW across different sectors. SWORM's activities include research and development, policy formulation, and the creation of action plans to mitigate space weather risks. A significant product of SWORM is the National Space Weather Action Plan. This plan outlines strategies and actions for improving the nation's resilience to SW events. It focuses on enhancing forecasting capabilities, protecting critical infrastructure, and developing response and recovery procedures for SW incidents.

EMP WG

The NRC assembled an internal working group in January 2019 to coordinate internal agency EMP efforts. The purpose of this effort has been to provide information on EMP effects on NPPs, respond to EO 13865, and determine any additional NRC actions on EMP.

NOAA Space Weather Prediction Center and Space Weather Scales

The NOAA Space Weather Prediction Center (SWPC)[29], formerly known as the Space Environment Center until 2007, operates as a laboratory and service center within the US National Weather Service, which is a part of the NOAA. Located in Boulder, Colorado, SWPC plays a critical role in monitoring and forecasting Earth's space environment, and it is recognized as the official source of space weather alerts and warnings in the United States.

[28] http://www.empcommission.org/docs/empc_exec_rpt.pdf
[29] https://www.swpc.noaa.gov/

The center's mission encompasses real-time monitoring and forecasting of solar and geophysical events. It conducts research in solar-terrestrial physics (heliophysics) and develops techniques for forecasting these disturbances. The SWPC Forecast Center operates jointly with NOAA and the US Air Force. It serves as a national and world warning center for SW disturbances. The center's services are important to various sectors including the US power grid, commercial aviation, the Department of Transportation (especially for GPS usage), NASA human space flight activities, satellite operations, and the US Space Force. The SWPC also collaborates with numerous national and international partners contributing data and observations.

SWPC can directly contact the NRC and licensees to provide notification of SW events as appropriate. Additional notification methods including automated emails are also publicly available. Individuals and organizations can subscribe to receive these SWPC notifications[30].

The NOAA Space Weather Scales are designed to inform the public about current and future SW conditions and their potential effects on people and systems. These scales are similar to those used for natural disasters like hurricanes and earthquakes, conveying the severity of SW events in terms of three categories: geomagnetic storms, solar radiation storms, and radio blackouts. Each category has a scale with numbered levels indicating the intensity of the event and its potential impacts.

- Geomagnetic Storms (G-scale): These storms can affect power systems, spacecraft operations, and other systems like pipelines and radio communications. The scale ranges from G1 (Minor) to G5 (Extreme), with G5 storms potentially causing widespread voltage control problems and power grid failures.
- Solar Radiation Storms (S-scale): This scale measures the potential biological impact on astronauts and passengers in high-flying aircraft, as well as effects on satellite operations and high frequency radio communications. The levels range from S1 (Minor) to S5 (Extreme), with S5 storms posing an unavoidable high radiation hazard to astronauts and potentially rendering satellites useless.
- Radio Blackouts (R-scale): These blackouts impact HF radio communication and navigation. The scale ranges from R1 (Minor), causing weak or minor degradation of HF radio communication, to R5 (Extreme), leading to complete HF radio blackout on the sunlit side of Earth for several hours.

As of January 2024, a discussion is underway to revise these scales. The goal is to provide more appropriate information in a timely manner that will assist users in preparing for, mitigating and recovering from events. Additionally, as a greater

[30] https://www.swpc.noaa.gov/content/subscription-services

understanding of the potential strength and impact of the various SW events is developed, realigning the scales to reflect actual severity is considered prudent.

NASA Capabilities in Modeling and Simulating SW Events

NASA has developed sophisticated capabilities for modeling and simulating SW events. These capabilities are important for understanding the dynamics of SW events and predicting their impacts on Earth.

NASA's Community Coordinated Modeling Center (CCMC)[31] is a key resource in this regard. The CCMC provides advanced scientific simulations of the solar system, including the Sun's magnetic field, solar wind, and geomagnetic storms. These simulations help researchers understand the complex processes involved in SW events and their potential impacts on Earth. Two of the models and simulations are listed below:

- efieldtool[32] calculates the geoelectric field using one-dimensional or three-dimensional ground conductivity. This information is relevant to GICs. The tool can utilize recorded historical USGS station data as well as observed geomagnetic field data.
- ENLIL[33] is a 3D Magnetohydrodynamic (MHD) model of the heliosphere and simulates the solar wind and CMEs from the Sun to beyond the orbit of Earth (from 2 AU up to 10 AU). This model helps forecast the arrival time and impact of CMEs on Earth, providing valuable information for mitigating the effects of SW events.

Satellite Observatories

Satellite observatories and assets play an important role in monitoring SW events, issuing early warnings, and facilitating research to understand the impacts on Earth's technological systems, including the power grid. Entities such as NASA and NOAA operate a fleet of advanced satellites that provide data relevant to solar activity, GMDs, and GICs.

Some current operational satellites include:

- NOAA's SWPC operates the Geostationary Operational Environmental Satellites (GOES) series, which orbit in geostationary positions. These satellites monitor solar and geomagnetic activity, providing real-time observations of the sun's surface and solar flares, which can indicate the likelihood of CMEs impacting Earth.
- NASA's Solar Dynamics Observatory (SDO) offers comprehensive observations of the sun, including its magnetic field, solar flares, and CMEs. By capturing high-

[31] https://ccmc.gsfc.nasa.gov/
[32] https://ccmc.gsfc.nasa.gov/models/efieldtool~1.1
[33] https://ccmc.gsfc.nasa.gov/models/ENLIL~2.8f

resolution images of the sun in multiple wavelengths, SDO aids in understanding the sun's influence on SW and its potential impact.

- NASA’s Advanced Composition Explorer (ACE), positioned at the L1 Lagrange point between Earth and the sun, gives an early warning of incoming solar wind streams and CMEs. ACE measures the speed, density, and magnetic field of solar wind particles, providing valuable data for predicting GMDs and GICs.

The data from these satellites assists in the assessment of SW event intensity and potential impacts. For example, GOES satellites measure the X-ray flux from solar flares, which helps in categorizing the flares' strength (ranging from class C, M, to X, with X being the most intense). Such categorization assists in evaluating the potential severity of SW events.

ACE's measurements of solar wind parameters allow for the estimation of the arrival time and potential impact strength of CMEs, giving insights into possible GMD and GIC effects on electrical power systems.

Earthbound Monitors

To increase their situational awareness, grid operators place earthbound magnetometers and GIC monitors in strategic locations along power lines. These tools provide valuable data to support real-time assessment of SW impacts on the electrical grid, enabling the employment of mitigating actions and proactive measures to safeguard the grid infrastructure.

Earthbound magnetometers measure variations in the Earth's magnetic field, providing critical data on geomagnetic disturbances (GMDs) caused by SW events. By analyzing this data, grid operators can detect the onset of GMDs, assess their intensity, and predict their potential impact on power grid operations. This information is important for activating emergency protocols and making informed decisions on grid management to prevent transformer damage, power outages, and other operational disruptions.

GIC monitors, installed directly on power lines, measure the actual currents induced by geomagnetic disturbances flowing through the grid. These measurements offer insights into the real-time effects of SW events on the power system. By understanding the magnitude and distribution of GICs, operators can identify vulnerable components, allocate resources effectively, and implement strategies to mitigate the risk of equipment failure and service interruption.

Spent Fuel Pools and High Assay Low Enriched Uranium (HALEU) Fuel

Spent fuel pools are used to store used nuclear fuel that is no longer efficient in sustaining a nuclear reaction. The pools keep the fuel cool and provide shielding from radiation.

A disruption in the cooling of spent fuel pools due to an EMP event could theoretically lead to the water in the pools boiling off, potentially exposing the fuel and leading to additional consequences. Such an event could also lead to the release of radiation.

However, these potential concerns for the spent fuel pools are not just related to the EMP initiator. The potential for a loss of cooling and the associated impacts have been evaluated in great detail. Any changes to the underlying assumptions used in the evaluation for spent fuel pools would be sufficiently analyzed prior to any approval for the modifications to ensure safety. Therefore, existing procedures already in place for spent fuel pools are considered sufficient to properly mitigate the risk or threat of an EMP event.

There is a potential for using higher enriched/HALEU fuels to extend fuel cycles and reduce waste. Such use would first be evaluated given the additional heat load that may be placed on spent fuel pools. Any resulting revisions to procedures would continue to provide sufficient mitigation for an EMP event.