UNITED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

Complaint and Petition of the Center for Security	)	
Policy and the Secure the Grid Coalition to	)	
Authorize Cost Recovery for Utilities That Assess	)	**Docket No. _____**
And Protect the Electric Grid from GIC	)	
To the International Standard of 85 V/km	)	

<u>**COMPLAINT AND PETITION**</u>
Submitted to FERC on March 9, 2026

Introduction:

The Center for Security Policy (CSP) is a non-profit, non-partisan 501(c)(3) organization whose mission is to provide uncompromised national security analysis and solutions to keep Americans safer. The Secure the Grid (STG) Coalition is a group of national security, energy policy and technical experts, focused on the security of the electric grid. Neither the CSP nor the STG Coalition receive any funding from governments, foreign sources, or industries and companies that can profit from our policy recommendations. We exist purely to support the public interest and national security of the United States. The members of the Secure the Grid Coalition also are electric utility ratepayers and would be adversely impacted by a failure of the Bulk Power System. Ground induced current ("GIC") from both solar weather and E3 HEMP threaten our electric power grid.

We are filing this complaint under 16 U.S. Code § 824o(d)(5)[1] because:

1) The current NERC standard for GIC protection[2] is inadequate.
2) The electric utility industry must be incentivized by cost recovery to protect the grid from GIC to the Department of Energy recommendations,[3] Congressional EMP Commission recommendations[4], and

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[1] "The Commission, upon its own motion *or upon complaint*, may order the Electric Reliability Organization to submit to the Commission a proposed reliability standard or a modification to a reliability standard that addresses a specific matter if the Commission considers such a new or modified reliability standard appropriate to carry out this section." [Emphasis added.]

[2] NERC TPL-007-4 – Transmission System Planned Performance for Geomagnetic Disturbance Events. October 1, 2020. (Attached hereto as Exhibit A.)

[3] "Physical Characteristics of HEMP Waveform Benchmarks for Use in Assessing Susceptibilities of the Power Grid, Electrical Infrastructures, and Other Critical Infrastructure to HEMP Insults" U.S. Department of Energy. January 11, 2021. (Attached hereto as Exhibit C.)

[4] "Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures." Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. July 2017. (Attached hereto as Exhibit D.)

the International Electrotechnical Commission (IEC) Standard[5] and to avoid exceeding the IEEE 519 Standard[6] due to GIC induced harmonics which is costing the U.S. economy billions of dollars each year.

Request for Investigation:

We request that the Commission issue a public notice of this Complaint pursuant to 18 CFR § 385.206(d), investigate this Complaint and issue an appropriate order to the Electric Reliability Organization ("ERO") to harden the bulk power system from GIC damage caused by GMD and E3 HEMP by specifying that rate recovery is approved for assessing and hardening the system to 85 V/km.

Background:

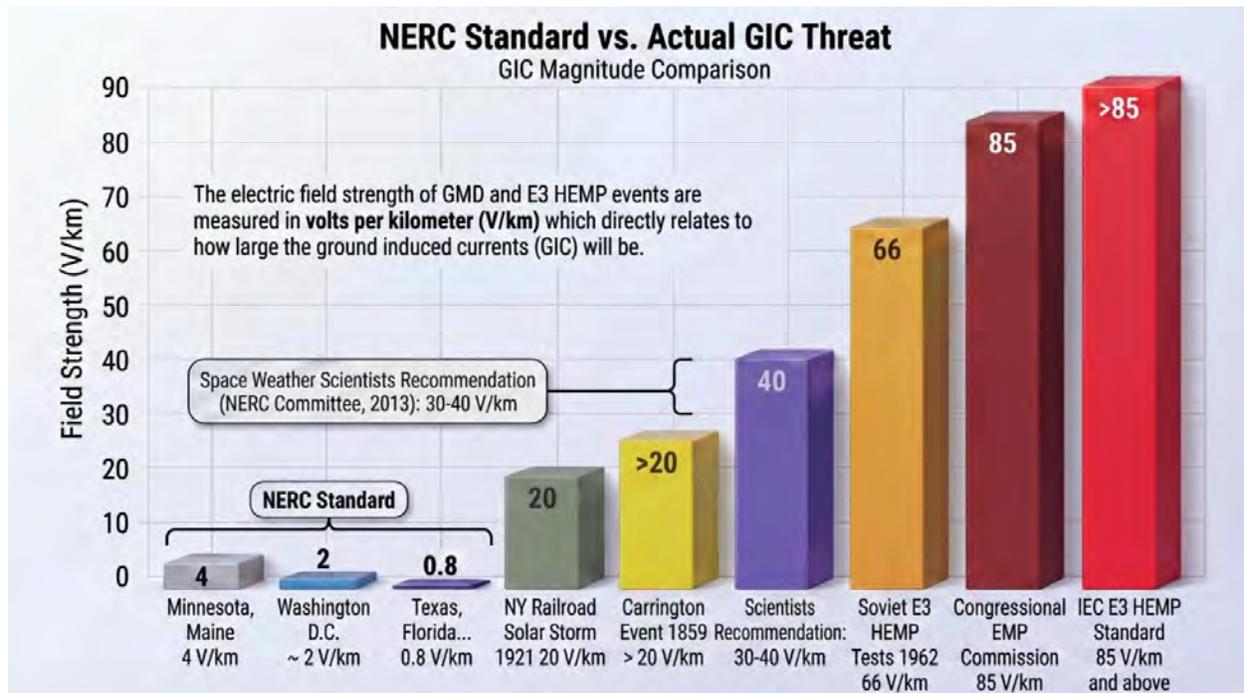As shown in Figure 1, the current NERC standard does not protect the electric grid from the GIC threat:

Figure 1

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[5] "Standard late-time HEMP waveform, International Electrotechnical Commission IEC 61000-2-9, Edition 2.0, 2025-05 (Abstract attached hereto as Exhibit E, entire standard incorporated by reference.)

[6] "IEEE Standard for Harmonic Control in Electric Power Systems," in IEEE Std 519-2022 (Revision of IEEE Std 519-2014), vol., no., pp.1-31, August 5, 2022. (Abstract attached hereto as Exhibit B. entire standard incorporated by reference)

Credible studies conclude that our electric grid suffers an estimated $10 billion <u>every year</u> due to GIC triggered harmonic anomalies in the electric grid.[7] [8] [9]

For a one-time investment of approximately $4 billion, the U.S. could not only stop this $10 billion annual economic loss but would also permanently protect the electric grid from the GIC hazards associated with severe space weather and High-Altitude Electromagnetic Pulse (HEMP).[10]

NERC TPL-007-4 is a consensus-based document - the lowest common denominator to achieve sufficient votes by the regulated industry. The standard does not protect against Ground Induced Currents (GIC), the half-cycle saturation of transformers and the resulting harmonics which routinely damage equipment in the Bulk Power System. [11]

On May 16, 2013, the Federal Energy Regulatory Commission (FERC) issued Order No. 779, directing the North American Electric Reliability Corporation (NERC) to develop mandatory reliability standards to mitigate the risks of geomagnetic disturbances (GMD) on the Bulk-Power System. However, NERC's "model" (written by the industry) purposely excluded the 1921 storm which produced 20 V/km.[12] The standard was intended to address a one in 100-year GMD event but did not include the largest solar storm in the 100-year period (the 1921 storm). Thus, the NERC standard failed to address one in 100-year GMD event.

GIC blocking devices attached to the neutral of a transformer exist and have been proven and validated both in the United States as well as internationally.[13]

The Center for Security Policy and the Secure the Grid Coalition have submitted several research papers to the Department of Energy on the issue of GIC protection for the electric grid and now submits these to the Commission for the record.[14] [15] [16]

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[7] U.S. Senate Committee on Homeland Security and Government Affairs, Statement by Dr. Justin Kasper. February 27, 2019. (Attached hereto as Exhibit F.)

[8] "Electrical Claims and Space Weather: Measuring the visible effects of an invisible force." Zurich Risk Engineering, Lockheed Martin Advanced Technology Center. June 2015. (Attached hereto as Exhibit G.)

[9] "Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment." C. J. Schrijver, R. Dobbins, W. Murtagh, and S. M. Petrinec. July 8, 2014. (Attached hereto as Exhibit H.)

[10] See page 63: "Estimating the Cost of Protecting the U.S. Electric Grid from Electromagnetic Pulse." Foundation for Resilient Societies. September 2020.

[11] NERC TPL-007-4 "Transmission System Planned Performance for Geomagnetic Disturbance Events." (Attached hereto as Exhibit A.)

[12] "Benchmark Geomagnetic Disturbance Event Description" Project 2013-03. GMD Mitigation Standard Drafting Team. May 12, 2016. (Attached hereto as Exhibit Q.)

[13] "Protecting the grid from solar storms." Western Area Power Administration. April 2023. . (Attached hereto as Exhibit J.)

[14] "Speed to Power on a Firm Foundation: Overcoming Dangerous Assumptions That Put America's Future at Risk." Center for Security Policy. November 2025. (Attached hereto as Exhibit K.)

[15] Comments of Secure the Grid Coalition on DOE "Speed to Power" RFI (2025-18058). Secure the Grid Coalition. November 21, 2025. (Attached hereto as Exhibit L.)

[16] Addendum on China, re: Secure the Grid Coalition's DOE "Speed to Power" RFI Response. Secure the Grid Coalition. January 12, 2026. (Attached hereto as Exhibit M.)

National reliance on large "data centers" to power Artificial Intelligence (AI) tools is increasing.[17] Both the U.S. Economy and the Defense Department will require reliable power to Data Centers that could be interrupted by GIC events. On March 1, 2026, The Wall Street Journal reported: "Data centers are equipped with technologies that monitor for disturbances on the grid that could cause a power outage and affect operations. When disturbances occur, many data centers automatically shift to backup supplies, severing their grid connections until power quality stabilizes."[18] The sudden and unexpected loss of thousands of megawatts of data center demand during a GIC event will further stress our unprotected grid.

On May 7, 2025, the Nuclear Regulatory Commission (NRC) published in the federal register[19] an extremely consequential decision with respect to the health, safety, and welfare of the American people and the environment of the continental United States. After more than fourteen years of deliberation, NRC denied an important Petition for Rulemaking submitted in February 2011, by the Foundation for Resilient Societies[20]. This Petition, docketed as PRM 50-96,[21] warned of the potentially catastrophic consequences associated with the long-term loss of offsite power for nuclear power plants, a realistic scenario given the vulnerability of America's electric grid to ground induced currents ("GIC") as a result of geomagnetic disturbances (GMDs) produced by the sun and intentional high-altitude electromagnetic pulse (E3 HEMP) attack by enemies of the United States.

Were a major solar storm to blackout the nation's grid for an extended period, numerous nuclear sites could be at risk of this scenario if their emergency diesel generators fail or run out of fuel. Thus, NERC's inadequate TPL-007-4 puts the United States at risk of a GIC induced nuclear disaster.[22]

We point out to the Commission that utility "Operating Procedures" cannot prevent GIC from entering an operating grid and are dangerously insufficient to protect the system from severe GIC. "Operating procedures" - including VAR supply and load shedding - will ensure grid components are exposed to more severe GIC and harmonics over a longer duration prior to failure, putting critical components at greater risk of permanent damage. The AC circuit breakers these procedures rely on are not designed to operate with GIC across them. As high-voltage circuit breakers begin to trip intentionally due to operating procedures or automatically due to effects of voltage collapse, there is considerable uncertainty regarding their ability to interrupt significant levels of GIC and harmonic currents. This is a dangerous misapplication and has never been tested. Failure to interrupt would lead to catastrophic

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[17] Executive Order 14318. "Accelerating Federal Permitting of Data Center Infrastructure." July 23, 2025. (Attached hereto as Exhibit N.)

[18] "A New Threat to Power Grids: Data Centers Unplugging at Once: Dozens of data centers abruptly dropped off the power grid in recent Virginia incidents, forcing operators to take emergency action." Wall Street Journal. March 1, 2026. Attached hereto as Exhibit O.)

[19] NRC Ruling, "Long-Term Cooling and Unattended Water Makeup of Spent Fuel Pools," https://www.federalregister.gov/documents/2025/05/07/2025-07899/long-term-cooling-and-unattended-water-makeup-of-spent-fuel-pools (Incorporated by reference).

[20] Homepage: Foundation for Resilient Societies, https://www.resilientsocieties.org/

[21] Foundation for Resilient Societies, In the Matter of a Proposed Rulemaking Regarding Amendment of 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities" https://www.resilientsocieties.org/uploads/5/4/0/0/54008795/petition_for_rulemaking_resilient_societies_docketed.pdf (Incorporated by reference).

[22] "Electric Reliability Standards for Solar Geomagnetic Disturbances." Comments submitted to the Federal Energy Regulatory Commission by Thomas S. Popik, George H. Baker, and William R. Harris. June 2017. (Attached hereto as Exhibit P.)

failure in the arcing chamber which contains over 100 pounds of SF6 gas - the world's most toxic greenhouse gas – releasing it into the environment. Load shedding increases this risk to high-voltage breakers even further, as it lowers the AC current across them which enhances the GIC bias. Each destroyed circuit breaker means a prolonged blackout for large sections of the grid. Self-induced "load shedding procedures" to shut the entire grid down, will themselves result in extremely prolonged blackouts. Nevertheless, industry lobbyists consistently placate lawmakers and executive branch officials with these "operating procedures" and "load shedding" arguments, but in reality, this is "a great experiment" that has never been conducted and one that would cause catastrophic harm to the grid and to the American people.

Finally, we bring to the Commission's attention Exhibit K, "Appendix II - Myths Vs Facts on GICs from GMD/HEMP." There is a series of myths that the self-regulator (NERC) and the utility industry propagate to avoid legislative or administrative action to protect the grid. This is a simple problem with simple solutions. The industry has a long history of trying to complicate the simple to avoid regulation. We implore the Commission not to fall into the industry's "complication trap."

Conclusion:

It is in the public interest as well as in the national security interest of the United States to assess the vulnerability of transformers and the power grid to the established international standard of 85 V/km and to protect the vulnerable transformers with proven and tested GIC blocking technology.

Relief Sought:

The Federal Energy Regulatory Commission should direct the North American Electric Reliability Corporation (NERC) to conduct a comprehensive survey of all registered entities in the Bulk Power System:

1. Each registered entity shall, no later than a date determined by the Commission, conduct a technical assessment of all covered equipment to determine vulnerability to GICs. The assessment shall:

    (a) Utilize the waveform in Figure A.5 of IEC 61000-2-9, Edition 2.0 (2025-05), modeling a peak magnetic field strength of 20,000 nT, or the corresponding waveform in Figure 9, modeling a peak electric field of 85 V/km.
    (b) Assume transformers are fully loaded during GIC exposure.
    (c) Account for transformer age and condition using ANSI/IEEE Standard C57.110 and IEEE Standard C57.91.
    (d) Identify susceptibility to half-cycle saturation, GIC-induced harmonics, reactive power consumption, hot spot generation, and insulation degradation.

2. The Commission should provide cost recovery for assessment and GIC protection to 85 V/km.

Respectfully submitted,

Tommy Waller
Lt. Col., USMC Ret.
President and CEO
Center for Security Policy

Douglas Ellsworth
Co-Director
Secure the Grid Coalition

Michael Mabee
Command SgtMaj, US Army Ret.
Principal Investigator
Secure the Grid Coalition

Attachments: 18 CFR § 385.206 Compliance Information
Draft Notice
Exhibit A: NERC TPL-007-4 – Transmission System Planned Performance for Geomagnetic Disturbance Events. October 1, 2020.
Exhibit B: Abstract from "IEEE Standard for Harmonic Control in Electric Power Systems," in IEEE Std 519-2022 (Revision of IEEE Std 519-2014), vol., no., pp.1-31, August 5, 2022. (Entire standard incorporated by reference.)
Exhibit C: "Physical Characteristics of HEMP Waveform Benchmarks for Use in Assessing Susceptibilities of the Power Grid, Electrical Infrastructures, and Other Critical Infrastructure to HEMP Insults" U.S. Department of Energy. January 11, 2021.
Exhibit D: "Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures." Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. July 2017.
Exhibit E: Abstract from "Standard late-time HEMP waveform, International Electrotechnical Commission IEC 61000-2-9, Edition 2.0, 2025-05 (Entire standard incorporated by reference).
Exhibit F: U.S. Senate Committee on Homeland Security and Government Affairs, Statement by Dr. Justin Kasper. February 27, 2019.
Exhibit G "Electrical Claims and Space Weather: Measuring the visible effects of an invisible force." Zurich Risk Engineering, Lockheed Martin Advanced Technology Center. June 2015.
Exhibit H: "Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment." C. J. Schrijver, R. Dobbins, W. Murtagh, and S. M. Petrinec. July 8, 2014.
Exhibit I: "Estimating the Cost of Protecting the U.S. Electric Grid from Electromagnetic Pulse." Foundation for Resilient Societies. September 2020. And: "Protecting U.S. Electric Grid Communications from Electromagnetic Pulse." Foundation for Resilient Societies. May 2020.
Exhibit J: "Protecting the grid from solar storms." Western Area Power Administration. April 2023.
Exhibit K: "Speed to Power on a Firm Foundation: Overcoming Dangerous Assumptions That Put America's Future at Risk." Center for Security Policy. November 2025.
Exhibit L: Comments of Secure the Grid Coalition on DOE "Speed to Power" RFI (2025-18058). Secure the Grid Coalition. November 21, 2025.
Exhibit M: Addendum on China, re: Secure the Grid Coalition's DOE "Speed to Power" RFI Response. Secure the Grid Coalition. January 12, 2026.
Exhibit N: Executive Order 14318. "Accelerating Federal Permitting of Data Center Infrastructure." July 23, 2025.

Exhibit O; "A New Threat to Power Grids: Data Centers Unplugging at Once: Dozens of
        data centers abruptly dropped off the power grid in recent Virginia incidents,
        forcing operators to take emergency action." Wall Street Journal. March 1,
        2026.
Exhibit P: "Electric Reliability Standards for Solar Geomagnetic Disturbances."
        Comments submitted to the Federal Energy Regulatory Commission by
        Thomas S. Popik, George H. Baker, and William R. Harris. June 2017
        Exhibit Q: "Benchmark Geomagnetic Disturbance Event Description" Project
        2013-03. GMD Mitigation Standard Drafting Team. May 12, 2016.
Exhibit Q: "Benchmark Geomagnetic Disturbance Event Description" Project 2013-03.
        GMD Mitigation Standard Drafting Team. NERC. May 12, 2016.

18 CFR § 385.206 Compliance Information

We Tommy Waller, Douglas Ellsworth, and Michael Mabee, hereby state the following:

18 CFR § 385.206(b) Contents. A complaint must:
(1) Clearly identify the action or inaction which is alleged to violate applicable statutory standards or regulatory requirements;

- The threat to reliability posed by GIC induced half-cycle saturation and GIC-induced harmonics is not addressed by NERC TPL-007-4.

(2) Explain how the action or inaction violates applicable statutory standards or regulatory requirements;

- The threat to reliability posed by GIC induced half-cycle saturation and GIC-induced harmonics is not addressed by NERC TPL-007-4.

(3) Set forth the business, commercial, economic or other issues presented by the action or inaction as such relate to or affect the complainant;

- The Commission should provide cost recovery for testing and GIC protection to 85 V/km.
- GIC blocking devices attached to the neutral of a transformer exist and have been proven and validated both in the United States as well as internationally.
- An estimated $10 billion is lost annually from routine GIC-induced harmonics damage and power interruption due to space weather.
- A one-time investment to install GIC blocking devices will not only stop the annual damage from space weather but would also protect against catastrophic damage from large solar storms (coronal mass ejections).
- Utility companies should be incentivized by cost recovery for surveying their systems and protecting their equipment to 85 V/km.

(4) Make a good faith effort to quantify the financial impact or burden (if any) created for the complainant as a result of the action or inaction;

- As an electric ratepayer and citizen of the United States, myself and fellow rate payers and citizens, as well as investors, are impacted by an estimated $10 billion annually from routine GIC-induced harmonics damage due to space weather.
- It is in the public interest, as well as in the interest of the utilities to protect the grid from GIC-induced damage.
- A widespread power outage due to GIC harmonic damage from solar weather or E3 HEMP would have a devastating impact on the U.S. economy and also cause a substantial loss of life.
- Even short-term GIC-induced power interruptions to data centers could have a devastating impact to the American economy.

(5) Indicate the practical, operational, or other nonfinancial impacts imposed as a result of the action or inaction, including, where applicable, the environmental, safety or reliability impacts of the action or inaction;

- A widespread power outage due to GIC-induced damage would have a devastating impact on the U.S. economy as well as substantial loss of life and impact to the environment. For example, major wastewater treatment plants might cease to function.

(6) State whether the issues presented are pending in an existing Commission proceeding or a proceeding in any other forum in which the complainant is a party, and if so, provide an explanation why timely resolution cannot be achieved in that forum;

- We are unaware of any public FERC docket which addresses the threats presented by the GIC-induced damage to the Bulk Power System from severe GIC levels and the catastrophic harmonic currents injected into the grid by many transformers across the grid that are simultaneously half-cycle saturating.

(7) State the specific relief or remedy requested, including any request for stay or extension of time, and the basis for that relief;

- Contained in "Relief Sought" section of Complaint.

(8) Include all documents that support the facts in the complaint in possession of, or otherwise attainable by, the complainant, including, but not limited to, contracts and affidavits;

- We have attached all supporting facts as exhibits to the Complaint.
- We affirm that this Complaint is being filed to support the public interest and national security of the United States of America and that neither we nor our Center for Security Policy receive funding from electric utilities or the companies that seek to protect these utilities.

(9) State

(i) Whether the Enforcement Hotline, Dispute Resolution Service, tariff-based dispute resolution mechanisms, or other informal dispute resolution procedures were used, or why these procedures were not used;

- N/A

(ii) Whether the complainant believes that alternative dispute resolution (ADR) under the Commission's supervision could successfully resolve the complaint;

- N/A

(iii) What types of ADR procedures could be used; and

- N/A

(iv) Any process that has been agreed on for resolving the complaint.

- N/A

(10) Include a form of notice of the complaint suitable for publication in the Federal Register in accordance with the specifications in § 385.203(d) of this part. The form of notice shall be on electronic media as specified by the Secretary.

- Draft Notice Attached

(11) Explain with respect to requests for Fast Track processing pursuant to section 385.206(h), why the standard processes will not be adequate for expeditiously resolving the complaint.

- N/A

18 CFR § 385.206(c) Service. Any person filing a complaint must serve a copy of the complaint on the respondent, affected regulatory agencies, and others the complainant reasonably knows may be expected to be affected by the complaint. Service must be simultaneous with filing at the Commission for respondents. Simultaneous or overnight service is permissible for other affected entities. Simultaneous service can be accomplished by electronic mail in accordance with § 385.2010(f)(3), facsimile, express delivery, or messenger.

- A copy of this Complaint will be sent electronically to the North American Electric Reliability Corporation (NERC) simultaneously with my filing with the Commission.

Respectfully submitted,

Tommy Waller
Lt. Col., USMC Ret
President and CEO
Center for Security Policy

Douglas Ellsworth
Co-Director
Secure the Grid Coalition

Michael Mabee
Command SgtMaj, US Army Ret.
Principal Investigator
Secure the Grid Coalition

Draft Notice

UNITED STATES OF AMERICA
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And Protect the Electric Grid from GIC	)	
To the International Standard of 85 V/km	)	

NOTICE OF COMPLAINT

(   )

  Take notice that on [date filed], pursuant to section 215(d) of the Federal Power Act, 16 U.S.C. 824o(d) and Rule 206 of the Federal Energy Regulatory Commission's (Commission) Rules of Practice and Procedure, 18 CFR 385.206 (2019), the Center for Security Policy and the Secure the Grid Coalition, (Complainants) filed a formal complaint alleging: 1) The current NERC standard for GMD/GIC protection is inadequate. 2) The electric utility industry must be incentivized by cost recovery to protect the grid from GIC to the Department of Energy recommendations, Congressional EMP Commission recommendations , and the International Electrotechnical Commission (IEC) Standard and to avoid exceeding the IEEE 519 Standard due to GIC induced harmonics which is costing the U.S. economy billions of dollars each year.

  Complainant certifies that copies of the complaint were served on the contacts as listed on the Commission's list of Corporate Officials.

  Any person desiring to intervene or to protest this filing must file in accordance with Rules 211 and 214 of the Commission's Rules of Practice and Procedure (18 CFR 385.211 and 385.214). Protests will be considered by the Commission in determining the appropriate action to be taken but will not serve to make protestants parties to the proceeding. Any person wishing to become a party must file a notice of intervention or motion to intervene, as appropriate. The Respondent's answer and all interventions, or protests must be filed on or before the comment date. The Respondent's answer, motions to intervene, and protests must be served on the Complainants.

  The Commission encourages electronic submission of protests and interventions in lieu of paper using the "eFiling" link at http://www.ferc.gov. Persons unable to file electronically should submit an original and 5 copies of the protest or intervention to the Federal Energy Regulatory Commission, 888 First Street, NE, Washington, DC 20426.

  This filing is accessible on-line at http://www.ferc.gov, using the "eLibrary" link and is available for review in the Commission's Public Reference Room in Washington, DC.   There is an "eSubscription" link on the web site that enables subscribers to receive email notification when a document is added to a subscribed docket(s). For assistance with any FERC Online service, please email

FERCOnlineSupport@ferc.gov, or call (866) 208-3676 (toll free). For TTY, call (202) 502-8659.

Comment Date: 5:00 pm Eastern Time on (insert date).

[Typed Name],
Secretary.

Exhibit A

**NERC TPL-007-4 – Transmission System Planned Performance for Geomagnetic Disturbance Events.
October 1, 2020.**

A. Introduction

1. **Title:** Transmission System Planned Performance for Geomagnetic Disturbance Events

2. **Number:** TPL-007-4

3. **Purpose:** Establish requirements for Transmission system planned performance during geomagnetic disturbance (GMD) events.

4. **Applicability:**

   4.1. **Functional Entities:**

      4.1.1. Planning Coordinator with a planning area that includes a Facility or Facilities specified in 4.2;

      4.1.2. Transmission Planner with a planning area that includes a Facility or Facilities specified in 4.2;

      4.1.3. Transmission Owner who owns a Facility or Facilities specified in 4.2; and

      4.1.4. Generator Owner who owns a Facility or Facilities specified in 4.2.

   4.2. **Facilities:**

      4.2.1. Facilities that include power transformer(s) with a high side, wye-grounded winding with terminal voltage greater than 200 kV.

5. **Effective Date:** See Implementation Plan for TPL-007-4.

6. **Background:** During a GMD event, geomagnetically-induced currents (GIC) may cause transformer hot-spot heating or damage, loss of Reactive Power sources, increased Reactive Power demand, and Misoperation(s), the combination of which may result in voltage collapse and blackout.

B. Requirements and Measures

R1. Each Planning Coordinator, in conjunction with its Transmission Planner(s), shall identify the individual and joint responsibilities of the Planning Coordinator and Transmission Planner(s) in the Planning Coordinator's planning area for maintaining models, performing the study or studies needed to complete benchmark and supplemental GMD Vulnerability Assessments, and implementing process(es) to obtain GMD measurement data as specified in this standard. *[Violation Risk Factor: Lower] [Time Horizon: Long-term Planning]*

M1. Each Planning Coordinator, in conjunction with its Transmission Planners, shall provide documentation on roles and responsibilities, such as meeting minutes, agreements, copies of procedures or protocols in effect between entities or between departments of a vertically integrated system, or email correspondence that identifies an agreement has been reached on individual and joint responsibilities for maintaining models, performing the study or studies needed to complete benchmark and supplemental GMD Vulnerability Assessments, and implementing process(es) to obtain GMD measurement data in accordance with Requirement R1.

R2. Each responsible entity, as determined in Requirement R1, shall maintain System models and GIC System models of the responsible entity's planning area for performing the study or studies needed to complete benchmark and supplemental GMD Vulnerability Assessments. *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*

M2. Each responsible entity, as determined in Requirement R1, shall have evidence in either electronic or hard copy format that it is maintaining System models and GIC System models of the responsible entity's planning area for performing the study or studies needed to complete benchmark and supplemental GMD Vulnerability Assessments.

R3. Each responsible entity, as determined in Requirement R1, shall have criteria for acceptable System steady state voltage performance for its System during the GMD events described in Attachment 1. *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

M3. Each responsible entity, as determined in Requirement R1, shall have evidence, such as electronic or hard copies of the criteria for acceptable System steady state voltage performance for its System in accordance with Requirement R3.

Benchmark GMD Vulnerability Assessment(s)

R4. Each responsible entity, as determined in Requirement R1, shall complete a benchmark GMD Vulnerability Assessment of the Near-Term Transmission Planning Horizon at least once every 60 calendar months. This benchmark GMD Vulnerability Assessment shall use a study or studies based on models identified in Requirement R2, document assumptions, and document summarized results of the steady state analysis. *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*

4.1. The study or studies shall include the following conditions:

4.1.1. System On-Peak Load for at least one year within the Near-Term Transmission Planning Horizon; and

4.1.2. System Off-Peak Load for at least one year within the Near-Term Transmission Planning Horizon.

4.2. The study or studies shall be conducted based on the benchmark GMD event described in Attachment 1 to determine whether the System meets the performance requirements for the steady state planning benchmark GMD event contained in Table 1.

4.3. The benchmark GMD Vulnerability Assessment shall be provided: (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinators, and adjacent Transmission Planners within 90 calendar days of completion, and (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of completion of the benchmark GMD Vulnerability Assessment, whichever is later.

   4.3.1. If a recipient of the benchmark GMD Vulnerability Assessment provides documented comments on the results, the responsible entity shall provide a documented response to that recipient within 90 calendar days of receipt of those comments.

M4. Each responsible entity, as determined in Requirement R1, shall have dated evidence such as electronic or hard copies of its benchmark GMD Vulnerability Assessment meeting all of the requirements in Requirement R4. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has distributed its benchmark GMD Vulnerability Assessment: (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinators, and adjacent Transmission Planners within 90 calendar days of completion, and (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of completion of the benchmark GMD Vulnerability Assessment, whichever is later, as specified in Requirement R4. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email notices or postal receipts showing recipient and date, that it has provided a documented response to comments received on its benchmark GMD Vulnerability Assessment within 90 calendar days of receipt of those comments in accordance with Requirement R4.

R5. Each responsible entity, as determined in Requirement R1, shall provide GIC flow information to be used for the benchmark thermal impact assessment of transformers specified in Requirement R6 to each Transmission Owner and Generator Owner that owns an applicable Bulk Electric System (BES) power transformer in the planning area. The GIC flow information shall include: *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

   5.1. The maximum effective GIC value for the worst case geoelectric field orientation for the benchmark GMD event described in Attachment 1. This value shall be provided to the Transmission Owner or Generator Owner that owns each applicable BES power transformer in the planning area.

5.2. The effective GIC time series, GIC(t), calculated using the benchmark GMD event described in Attachment 1 in response to a written request from the Transmission Owner or Generator Owner that owns an applicable BES power transformer in the planning area. GIC(t) shall be provided within 90 calendar days of receipt of the written request and after determination of the maximum effective GIC value in Part 5.1.

M5. Each responsible entity, as determined in Requirement R1, shall provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided the maximum effective GIC values to the Transmission Owner and Generator Owner that owns each applicable BES power transformer in the planning area as specified in Requirement R5, Part 5.1. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided GIC(t) in response to a written request from the Transmission Owner or Generator Owner that owns an applicable BES power transformer in the planning area.

R6. Each Transmission Owner and Generator Owner shall conduct a benchmark thermal impact assessment for its solely and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A per phase or greater. The benchmark thermal impact assessment shall: *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

6.1. Be based on the effective GIC flow information provided in Requirement R5;

6.2. Document assumptions used in the analysis;

6.3. Describe suggested actions and supporting analysis to mitigate the impact of GICs, if any; and

6.4. Be performed and provided to the responsible entities, as determined in Requirement R1, within 24 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1.

M6. Each Transmission Owner and Generator Owner shall have evidence such as electronic or hard copies of its benchmark thermal impact assessment for all of its solely and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A per phase or greater, and shall have evidence such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided its thermal impact assessment to the responsible entities as specified in Requirement R6.

R7. Each responsible entity, as determined in Requirement R1, that concludes through the benchmark GMD Vulnerability Assessment conducted in Requirement R4 that their System does not meet the performance requirements for the steady state planning benchmark GMD event contained in Table 1, shall develop a Corrective

Action Plan (CAP) addressing how the performance requirements will be met. The CAP shall: *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*

7.1. List System deficiencies and the associated actions needed to achieve required System performance. Examples of such actions include:

- Installation, modification, retirement, or removal of Transmission and generation Facilities and any associated equipment.

- Installation, modification, or removal of Protection Systems or Remedial Action Schemes.

- Use of Operating Procedures, specifying how long they will be needed as part of the CAP.

- Use of Demand-Side Management, new technologies, or other initiatives.

7.2. Be developed within one year of completion of the benchmark GMD Vulnerability Assessment.

7.3. Include a timetable, subject to approval for any extension sought under Part 7.4, for implementing the selected actions from Part 7.1. The timetable shall:

7.3.1. Specify implementation of non-hardware mitigation, if any, within two years of development of the CAP; and

7.3.2. Specify implementation of hardware mitigation, if any, within four years of development of the CAP.

7.4. Be submitted to the Compliance Enforcement Authority (CEA) with a request for extension of time if the responsible entity is unable to implement the CAP within the timetable provided in Part 7.3. The submitted CAP shall document the following:

7.4.1. Circumstances causing the delay for fully or partially implementing the selected actions in Part 7.1 and how those circumstances are beyond the control of the responsible entity;

7.4.2. Revisions to the selected actions in Part 7.1, if any, including utilization of Operating Procedures, if applicable; and

7.4.3. Updated timetable for implementing the selected actions in Part 7.1.

7.5. Be provided: (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), and functional entities referenced in the CAP within 90 calendar days of development or revision, and (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of development or revision, whichever is later.

7.5.1. If a recipient of the CAP provides documented comments on the CAP, the responsible entity shall provide a documented response to that recipient within 90 calendar days of receipt of those comments.

M7. Each responsible entity, as determined in Requirement R1, that concludes, through the benchmark GMD Vulnerability Assessment conducted in Requirement R4, that the responsible entity's System does not meet the performance requirements for the steady state planning benchmark GMD event contained in Table 1 shall have evidence such as dated electronic or hard copies of its CAP including timetable for implementing selected actions, as specified in Requirement R7. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records or postal receipts showing recipient and date, that it submitted a request for extension to the CEA if the responsible entity is unable to implement the CAP within the timetable provided in Part 7.3. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has distributed its CAP or relevant information, if any, (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), and functional entities referenced in the CAP within 90 calendar days of development or revision, and (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of development or revision, whichever is later as specified in Requirement R7. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email notices or postal receipts showing recipient and date, that it has provided a documented response to comments received on its CAP within 90 calendar days of receipt of those comments, in accordance with Requirement R7.

Supplemental GMD Vulnerability Assessment(s)

R8. Each responsible entity, as determined in Requirement R1, shall complete a supplemental GMD Vulnerability Assessment of the Near-Term Transmission Planning Horizon at least once every 60 calendar months. This supplemental GMD Vulnerability Assessment shall use a study or studies based on models identified in Requirement R2, document assumptions, and document summarized results of the steady state analysis. *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*

8.1. The study or studies shall include the following conditions:

8.1.1. System On-Peak Load for at least one year within the Near-Term Transmission Planning Horizon; and

8.1.2. System Off-Peak Load for at least one year within the Near-Term Transmission Planning Horizon.

8.2. The study or studies shall be conducted based on the supplemental GMD event described in Attachment 1 to determine whether the System meets the performance requirements for the steady state planning supplemental GMD event contained in Table 1.

8.3. The supplemental GMD Vulnerability Assessment shall be provided: (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinators, adjacent Transmission Planners within 90 calendar days of completion, and (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of completion of the supplemental GMD Vulnerability Assessment, whichever is later.

8.3.1. If a recipient of the supplemental GMD Vulnerability Assessment provides documented comments on the results, the responsible entity shall provide a documented response to that recipient within 90 calendar days of receipt of those comments.

M8. Each responsible entity, as determined in Requirement R1, shall have dated evidence such as electronic or hard copies of its supplemental GMD Vulnerability Assessment meeting all of the requirements in Requirement R8. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has distributed its supplemental GMD Vulnerability Assessment: (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinators, adjacent Transmission Planners within 90 calendar days of completion, and (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of completion of the supplemental GMD Vulnerability Assessment, whichever is later, as specified in Requirement R8. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email notices or postal receipts showing recipient and date, that it has provided a documented response to comments received on its supplemental GMD Vulnerability Assessment within 90 calendar days of receipt of those comments in accordance with Requirement R8.

R9. Each responsible entity, as determined in Requirement R1, shall provide GIC flow information to be used for the supplemental thermal impact assessment of transformers specified in Requirement R10 to each Transmission Owner and Generator Owner that owns an applicable Bulk Electric System (BES) power transformer in the planning area. The GIC flow information shall include: *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

9.1. The maximum effective GIC value for the worst case geoelectric field orientation for the supplemental GMD event described in Attachment 1. This value shall be provided to the Transmission Owner or Generator Owner that owns each applicable BES power transformer in the planning area.

9.2. The effective GIC time series, GIC(t), calculated using the supplemental GMD event described in Attachment 1 in response to a written request from the Transmission Owner or Generator Owner that owns an applicable BES power transformer in the planning area. GIC(t) shall be provided within 90 calendar days of receipt of the written request and after determination of the maximum effective GIC value in Part 9.1.

M9. Each responsible entity, as determined in Requirement R1, shall provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided the maximum effective GIC values to the Transmission Owner and Generator Owner that owns each applicable BES power transformer in the planning area as specified in Requirement R9, Part 9.1. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided GIC(t) in response to a written request from the Transmission Owner or Generator Owner that owns an applicable BES power transformer in the planning area.

R10. Each Transmission Owner and Generator Owner shall conduct a supplemental thermal impact assessment for its solely and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R9, Part 9.1, is 85 A per phase or greater. The supplemental thermal impact assessment shall: *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

10.1. Be based on the effective GIC flow information provided in Requirement R9;

10.2. Document assumptions used in the analysis;

10.3. Describe suggested actions and supporting analysis to mitigate the impact of GICs, if any; and

10.4. Be performed and provided to the responsible entities, as determined in Requirement R1, within 24 calendar months of receiving GIC flow information specified in Requirement R9, Part 9.1.

M10. Each Transmission Owner and Generator Owner shall have evidence such as electronic or hard copies of its supplemental thermal impact assessment for all of its solely and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R9, Part 9.1, is 85 A per phase or greater, and shall have evidence such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided its supplemental thermal impact assessment to the responsible entities as specified in Requirement R10.

R11. Each responsible entity, as determined in Requirement R1, that concludes through the supplemental GMD Vulnerability Assessment conducted in Requirement R8 that their System does not meet the performance requirements for the steady state planning supplemental GMD event contained in Table 1, shall develop a Corrective

Action Plan (CAP) addressing how the performance requirements will be met. The CAP shall: *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*

11.1. List System deficiencies and the associated actions needed to achieve required System performance. Examples of such actions include:

- Installation, modification, retirement, or removal of Transmission and generation Facilities and any associated equipment.

- Installation, modification, or removal of Protection Systems or Remedial Action Schemes.

- Use of Operating Procedures, specifying how long they will be needed as part of the CAP.

- Use of Demand-Side Management, new technologies, or other initiatives.

11.2. Be developed within one year of completion of the supplemental GMD Vulnerability Assessment.

11.3. Include a timetable, subject to approval for any extension sought under Part 11.4, for implementing the selected actions from Part 11.1. The timetable shall:

11.3.1. Specify implementation of non-hardware mitigation, if any, within two years of development of the CAP; and

11.3.2. Specify implementation of hardware mitigation, if any, within four years of development of the CAP.

11.4. Be submitted to the CEA with a request for extension of time if the responsible entity is unable to implement the CAP within the timetable provided in Part 11.3. The submitted CAP shall document the following:

11.4.1. Circumstances causing the delay for fully or partially implementing the selected actions in Part 11.1 and how those circumstances are beyond the control of the responsible entity;

11.4.2. Revisions to the selected actions in Part 11.1, if any, including utilization of Operating Procedures, if applicable; and

11.4.3. Updated timetable for implementing the selected actions in Part 11.1.

11.5. Be provided: (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), and functional entities referenced in the CAP within 90 calendar days of development or revision, and (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of development or revision, whichever is later.

11.5.1. If a recipient of the CAP provides documented comments on the CAP, the responsible entity shall provide a documented response to that recipient within 90 calendar days of receipt of those comments.

M11. Each responsible entity, as determined in Requirement R1, that concludes, through the supplemental GMD Vulnerability Assessment conducted in Requirement R8, that the responsible entity's System does not meet the performance requirements for the steady state planning supplemental GMD event contained in Table 1 shall have evidence such as dated electronic or hard copies of its CAP including timetable for implementing selected actions, as specified in Requirement R11. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records or postal receipts showing recipient and date, that it submitted a request for extension to the CEA if the responsible entity is unable to implement the CAP within the timetable provided in Part 11.3. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has distributed its CAP or relevant information, if any, (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), and functional entities referenced in the CAP within 90 calendar days of development or revision, and (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of development or revision, whichever is later as specified in Requirement R11. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email notices or postal receipts showing recipient and date, that it has provided a documented response to comments received on its CAP within 90 calendar days of receipt of those comments, in accordance with Requirement R11.

GMD Measurement Data Processes

R12. Each responsible entity, as determined in Requirement R1, shall implement a process to obtain GIC monitor data from at least one GIC monitor located in the Planning Coordinator's planning area or other part of the system included in the Planning Coordinator's GIC System model. *[Violation Risk Factor: Lower] [Time Horizon: Long-term Planning]*

M12. Each responsible entity, as determined in Requirement R1, shall have evidence such as electronic or hard copies of its GIC monitor location(s) and documentation of its process to obtain GIC monitor data in accordance with Requirement R12.

R13. Each responsible entity, as determined in Requirement R1, shall implement a process to obtain geomagnetic field data for its Planning Coordinator's planning area. *[Violation Risk Factor: Lower] [Time Horizon: Long-term Planning]*

M13. Each responsible entity, as determined in Requirement R1, shall have evidence such as electronic or hard copies of its process to obtain geomagnetic field data for its Planning Coordinator's planning area in accordance with Requirement R13.

C. Compliance

1.   Compliance Monitoring Process

1.1. Compliance Enforcement Authority: "Compliance Enforcement Authority" means NERC or the Regional Entity, or any entity as otherwise designated by an Applicable Governmental Authority, in their respective roles of monitoring and/or enforcing compliance with mandatory and enforceable Reliability Standards in their respective jurisdictions.

1.2. Evidence Retention: The following evidence retention period(s) identify the period of time an entity is required to retain specific evidence to demonstrate compliance. For instances where the evidence retention period specified below is shorter than the time since the last audit, the Compliance Enforcement Authority may ask an entity to provide other evidence to show that it was compliant for the full-time period since the last audit.

The applicable entity shall keep data or evidence to show compliance as identified below unless directed by its Compliance Enforcement Authority to retain specific evidence for a longer period of time as part of an investigation.

- For Requirements R1, R2, R3, R5, R6, R9, and R10, each responsible entity shall retain documentation as evidence for five years.

- For Requirements R4 and R8, each responsible entity shall retain documentation of the current GMD Vulnerability Assessment and the preceding GMD Vulnerability Assessment.

- For Requirement R7 and R11, each responsible entity shall retain documentation as evidence for five years or until all actions in the Corrective Action Plan are completed, whichever is later.

- For Requirements R12 and R13, each responsible entity shall retain documentation as evidence for three years.

1.3. Compliance Monitoring and Enforcement Program: As defined in the NERC Rules of Procedure, "Compliance Monitoring and Enforcement Program" refers to the identification of the processes that will be used to evaluate data or information for the purpose of assessing performance or outcomes with the associated Reliability Standard.

Table 1: Steady State Planning GMD Event				
Steady State: a. Voltage collapse, Cascading and uncontrolled islanding shall not occur. b. Generation loss is acceptable as a consequence of the steady state planning GMD events. c. Planned System adjustments such as Transmission configuration changes and re-dispatch of generation are allowed if such adjustments are executable within the time duration applicable to the Facility Ratings.				
Category	**Initial Condition**	**Event**	**Interruption of Firm Transmission Service Allowed**	**Load Loss Allowed**
Benchmark GMD Event – GMD Event with Outages	1. System as may be postured in response to space weather information[1], and then 2. GMD event[2]	Reactive Power compensation devices and other Transmission Facilities removed as a result of Protection System operation or Misoperation due to harmonics during the GMD event	Yes[3]	Yes[3]
Supplemental GMD Event – GMD Event with Outages	1. System as may be postured in response to space weather information[1], and then 2. GMD event[2]	Reactive Power compensation devices and other Transmission Facilities removed as a result of Protection System operation or Misoperation due to harmonics during the GMD event	Yes	Yes
Table 1: Steady State Performance Footnotes				
1. The System condition for GMD planning may include adjustments to posture the System that are executable in response to space weather information. 2. The GMD conditions for the benchmark and supplemental planning events are described in Attachment 1. 3. Load loss as a result of manual or automatic Load shedding (e.g., UVLS) and/or curtailment of Firm Transmission Service may be used to meet BES performance requirements during studied GMD conditions. The likelihood and magnitude of Load loss or curtailment of Firm Transmission Service should be minimized.				

Violation Severity Levels

R #	Violation Severity Levels			
	Lower VSL	**Moderate VSL**	**High VSL**	**Severe VSL**
R1.	N/A	N/A	N/A	The Planning Coordinator, in conjunction with its Transmission Planner(s), failed to determine and identify individual or joint responsibilities of the Planning Coordinator and Transmission Planner(s) in the Planning Coordinator's planning area for maintaining models, performing the study or studies needed to complete benchmark and supplemental GMD Vulnerability Assessments, and implementing process(es) to obtain GMD measurement data as specified in this standard.
R2.	N/A	N/A	The responsible entity did not maintain either System models or GIC System models of the responsible entity's planning area for performing the studies	The responsible entity did not maintain both System models and GIC System models of the responsible entity's planning area for performing the studies

R #	Violation Severity Levels			
	Lower VSL	**Moderate VSL**	**High VSL**	**Severe VSL**
			needed to complete benchmark and supplemental GMD Vulnerability Assessments.	needed to complete benchmark and supplemental GMD Vulnerability Assessments.
R3.	N/A	N/A	N/A	The responsible entity did not have criteria for acceptable System steady state voltage performance for its System during the GMD events described in Attachment 1 as required.
R4.	The responsible entity completed a benchmark GMD Vulnerability Assessment, but it was more than 60 calendar months and less than or equal to 64 calendar months since the last benchmark GMD Vulnerability Assessment.	The responsible entity's completed benchmark GMD Vulnerability Assessment failed to satisfy one of the elements listed in Requirement R4, Parts 4.1 through 4.3; OR The responsible entity completed a benchmark GMD Vulnerability Assessment, but it was more than 64 calendar months and less than or equal to 68 calendar months since the	The responsible entity's completed benchmark GMD Vulnerability Assessment failed to satisfy two of the elements listed in Requirement R4, Parts 4.1 through 4.3; OR The responsible entity completed a benchmark GMD Vulnerability Assessment, but it was more than 68 calendar months and less than or equal to 72 calendar months since the	The responsible entity's completed benchmark GMD Vulnerability Assessment failed to satisfy three of the elements listed in Requirement R4, Parts 4.1 through 4.3; OR The responsible entity completed a benchmark GMD Vulnerability Assessment, but it was more than 72 calendar months since the last benchmark

R #	Violation Severity Levels			
	Lower VSL	**Moderate VSL**	**High VSL**	**Severe VSL**
		last benchmark GMD Vulnerability Assessment.	last benchmark GMD Vulnerability Assessment.	GMD Vulnerability Assessment; OR The responsible entity does not have a completed benchmark GMD Vulnerability Assessment.
R5.	The responsible entity provided the effective GIC time series, GIC(t), in response to written request, but did so more than 90 calendar days and less than or equal to 100 calendar days after receipt of a written request.	The responsible entity provided the effective GIC time series, GIC(t), in response to written request, but did so more than 100 calendar days and less than or equal to 110 calendar days after receipt of a written request.	The responsible entity provided the effective GIC time series, GIC(t), in response to written request, but did so more than 110 calendar days after receipt of a written request.	The responsible entity did not provide the maximum effective GIC value to the Transmission Owner and Generator Owner that owns each applicable BES power transformer in the planning area; OR The responsible entity did not provide the effective GIC time series, GIC(t), upon written request.
R6.	The responsible entity failed to conduct a benchmark thermal impact assessment for 5% or less or one of its solely owned and jointly owned applicable BES power	The responsible entity failed to conduct a benchmark thermal impact assessment for more than 5% up to (and including) 10% or two of its solely owned and jointly	The responsible entity failed to conduct a benchmark thermal impact assessment for more than 10% up to (and including) 15% or three of its solely owned and	The responsible entity failed to conduct a benchmark thermal impact assessment for more than 15% or more than three of its solely owned and jointly owned

R #	Violation Severity Levels			
	Lower VSL	**Moderate VSL**	**High VSL**	**Severe VSL**
	transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase; OR The responsible entity conducted a benchmark thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase but did so more than 24 calendar months and less than or equal to 26 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1.	owned applicable BES power transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase; OR The responsible entity conducted a benchmark thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase but did so more than 26 calendar months and less than or equal to 28 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1; OR The responsible entity failed to include one of the	jointly owned applicable BES power transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase; OR The responsible entity conducted a benchmark thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase but did so more than 28 calendar months and less than or equal to 30 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1; OR The responsible entity failed to include two of the	applicable BES power transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase; OR The responsible entity conducted a benchmark thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase but did so more than 30 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1; OR The responsible entity failed to include three of the required elements as listed

R #	Violation Severity Levels			
	Lower VSL	**Moderate VSL**	**High VSL**	**Severe VSL**
		required elements as listed in Requirement R6, Parts 6.1 through 6.3.	required elements as listed in Requirement R6, Parts 6.1 through 6.3.	in Requirement R6, Parts 6.1 through 6.3.
R7.	The responsible entity's Corrective Action Plan failed to comply with one of the elements in Requirement R7, Parts 7.1 through 7.5.	The responsible entity's Corrective Action Plan failed to comply with two of the elements in Requirement R7, Parts 7.1 through 7.5.	The responsible entity's Corrective Action Plan failed to comply with three of the elements in Requirement R7, Parts 7.1 through 7.5.	The responsible entity's Corrective Action Plan failed to comply with four or more of the elements in Requirement R7, Parts 7.1 through 7.5; OR The responsible entity did not develop a Corrective Action Plan as required by Requirement R7.
R8.	The responsible entity completed a supplemental GMD Vulnerability Assessment, but it was more than 60 calendar months and less than or equal to 64 calendar months since the last supplemental GMD Vulnerability Assessment.	The responsible entity's completed supplemental GMD Vulnerability Assessment failed to satisfy one of the elements listed in Requirement R8, Parts 8.1 through 8.3; OR The responsible entity completed a supplemental GMD Vulnerability Assessment, but it was more	The responsible entity's completed supplemental GMD Vulnerability Assessment failed to satisfy two of the elements listed in Requirement R8, Parts 8.1 through 8.3; OR The responsible entity completed a supplemental GMD Vulnerability Assessment, but it was more	The responsible entity's completed supplemental GMD Vulnerability Assessment failed to satisfy three of the elements listed in Requirement R8, Parts 8.1 through 8.3; OR The responsible entity completed a supplemental GMD Vulnerability Assessment, but it was more

R #	Violation Severity Levels			
	Lower VSL	**Moderate VSL**	**High VSL**	**Severe VSL**
		than 64 calendar months and less than or equal to 68 calendar months since the last supplemental GMD Vulnerability Assessment.	than 68 calendar months and less than or equal to 72 calendar months since the last supplemental GMD Vulnerability Assessment.	than 72 calendar months since the last supplemental GMD Vulnerability Assessment; OR The responsible entity does not have a completed supplemental GMD Vulnerability Assessment.
R9.	The responsible entity provided the effective GIC time series, GIC(t), in response to written request, but did so more than 90 calendar days and less than or equal to 100 calendar days after receipt of a written request.	The responsible entity provided the effective GIC time series, GIC(t), in response to written request, but did so more than 100 calendar days and less than or equal to 110 calendar days after receipt of a written request.	The responsible entity provided the effective GIC time series, GIC(t), in response to written request, but did so more than 110 calendar days after receipt of a written request.	The responsible entity did not provide the maximum effective GIC value to the Transmission Owner and Generator Owner that owns each applicable BES power transformer in the planning area; OR The responsible entity did not provide the effective GIC time series, GIC(t), upon written request.
R10.	The responsible entity failed to conduct a supplemental thermal impact assessment for 5% or less or one of its	The responsible entity failed to conduct a supplemental thermal impact assessment for more than 5% up to (and	The responsible entity failed to conduct a supplemental thermal impact assessment for more than 10% up to	The responsible entity failed to conduct a supplemental thermal impact assessment for more than 15% or more

R #	Violation Severity Levels			
	Lower VSL	**Moderate VSL**	**High VSL**	**Severe VSL**
	solely owned and jointly owned applicable BES power transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R9, Part 9.1, is 85 A or greater per phase; OR The responsible entity conducted a supplemental thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R9, Part 9.1, is 85 A or greater per phase but did so more than 24 calendar months and less than or equal to 26 calendar months of receiving GIC flow information specified in Requirement R9, Part 9.1.	including) 10% or two of its solely owned and jointly owned applicable BES power transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R9, Part 9.1, is 85 A or greater per phase; OR The responsible entity conducted a supplemental thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R9, Part 9.1, is 85 A or greater per phase but did so more than 26 calendar months and less than or equal to 28 calendar months of receiving GIC flow information specified in Requirement R9, Part 9.1 OR	(and including) 15% or three of its solely owned and jointly owned applicable BES power transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R9, Part 9.1, is 85 A or greater per phase; OR The responsible entity conducted a supplemental thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R9, Part 9.1, is 85 A or greater per phase but did so more than 28 calendar months and less than or equal to 30 calendar months of receiving GIC flow information specified in Requirement R9, Part 9.1; OR	than three of its solely owned and jointly owned applicable BES power transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R9, Part 9.1, is 85 A or greater per phase; OR The responsible entity conducted a supplemental thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R9, Part 9.1, is 85 A or greater per phase but did so more than 30 calendar months of receiving GIC flow information specified in Requirement R9, Part 9.1; OR

R #	Violation Severity Levels			
	Lower VSL	**Moderate VSL**	**High VSL**	**Severe VSL**
		The responsible entity failed to include one of the required elements as listed in Requirement R10, Parts 10.1 through 10.3.	The responsible entity failed to include two of the required elements as listed in Requirement R10, Parts 10.1 through 10.3.	The responsible entity failed to include three of the required elements as listed in Requirement R10, Parts 10.1 through 10.3.
R11.	The responsible entity's Corrective Action Plan failed to comply with one of the elements in Requirement R11, Parts 11.1 through 11.5.	The responsible entity's Corrective Action Plan failed to comply with two of the elements in Requirement R11, Parts 11.1 through 11.5.	The responsible entity's Corrective Action Plan failed to comply with three of the elements in Requirement R11, Parts 11.1 through 11.5.	The responsible entity's Corrective Action Plan failed to comply with four or more of the elements in Requirement R11, Parts 11.1 through 11.5; OR The responsible entity did not develop a Corrective Action Plan as required by Requirement R11.

R #	Violation Severity Levels			
	Lower VSL	**Moderate VSL**	**High VSL**	**Severe VSL**
R12.	N/A	N/A	N/A	The responsible entity did not implement a process to obtain GIC monitor data from at least one GIC monitor located in the Planning Coordinator's planning area or other part of the system included in the Planning Coordinator's GIC System Model.
R13.	N/A	N/A	N/A	The responsible entity did not implement a process to obtain geomagnetic field data for its Planning Coordinator's planning area.

D. Regional Variances

D.A. Regional Variance for Canadian Jurisdictions

This Variance shall be applicable in those Canadian jurisdictions where the Variance has been approved for use by the applicable governmental authority or has otherwise become effective in the jurisdiction.

This variance replaces all references to "Attachment 1" in the standard with "Attachment 1 or Attachment 1-CAN."

In addition, this Variance replaces Requirement R7, Part 7.3 through Part 7.5 and Requirement R11, Part 11.3 through Part 11.5 with the following:

D.A.7.3. Include a timetable, subject to revision by the responsible entity in Part D.A.7.4, for implementing the selected actions from Part 7.1. The timetable shall:

D.A.7.3.1. Specify implementation of non-hardware mitigation, if any, within two years of the later of the development of the CAP or receipt of regulatory approvals, if required; and

D.A.7.3.2. Specify implementation of hardware mitigation, if any, within four years of the later of the development of the CAP or receipt of regulatory approvals, if required.

D.A.7.4. Be revised if the responsible entity is unable to implement the CAP within the timetable for implementation provided in Part D.A.7.3. The revised CAP shall document the following:

D.A.7.4.1 Circumstances causing the delay for fully or partially implementing the selected actions in Part 7.1 and how those circumstances are beyond the control of the responsible entity;

D.A.7.4.2 Revisions to the selected actions in Part 7.1, if any, including utilization of Operating Procedures if applicable; and

D.A.7.4.3 Updated timetable for implementing the selected actions in Part 7.1.

D.A.7.5. Be provided: (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), and functional entities referenced in the CAP within 90 calendar days of development or revision, (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of development or revision, whichever is later, and (iii) to the Compliance Enforcement Authority or Applicable Governmental Authority when revised under D.A.7.4 within 90 calendar days of revision.

D.A.7.5.1 If a recipient of the CAP provides documented comments on the CAP, the responsible entity shall provide a documented response to that recipient within 90 calendar days of receipt of those comments.

D.A.M.7. Each responsible entity, as determined in Requirement R1, that concludes, through the benchmark GMD Vulnerability Assessment conducted in Requirement R4, that the responsible entity's System does not meet the performance requirements for the steady state planning benchmark GMD event contained in Table 1 shall have evidence such as dated electronic or hard copies of its CAP including timetable for implementing selected actions, as specified in Requirement R7. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records or postal receipts showing recipient and date, that it has revised its CAP if situations beyond the responsible entity's control prevent implementation of the CAP within the timetable specified. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has distributed its CAP or relevant information, if any, (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), and functional entities referenced in the CAP within 90 calendar days of development or revision, (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of development or revision, whichever is later as specified in Requirement R7, and (iii) to the Compliance Enforcement Authority or Applicable Governmental Authority when revised under D.A.7.4 within 90 calendar days of revision. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email notices or postal receipts showing recipient and date, that it has provided a documented response to comments received on its CAP within 90 calendar days of receipt of those comments, in accordance with Requirement R7.

D.A.11.3. Include a timetable, subject to revision by the responsible entity in Part D.A.11.4, for implementing the selected actions from Part 11.1. The timetable shall:

D.A.11.3.1. Specify implementation of non-hardware mitigation, if any, within two years of the later of the development of the CAP or receipt of regulatory approvals, if required; and

D.A.11.3.2. Specify implementation of hardware mitigation, if any, within four years of the later of the development of the CAP or receipt of regulatory approvals, if required.

D.A.11.4. Be revised if the responsible entity is unable to implement the CAP within the timetable for implementation provided in Part D.A.11.3. The revised CAP shall document the following:

D.A.11.4.1 Circumstances causing the delay for fully or partially implementing the selected actions in Part 11.1 and how those circumstances are beyond the control of the responsible entity;

D.A.11.4.2 Revisions to the selected actions in Part 11.1, if any, including utilization of Operating Procedures if applicable; and

D.A.11.4.3 Updated timetable for implementing the selected actions in Part 11.1.

D.A.11.5. Be provided: (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), and functional entities referenced in the CAP within 90 calendar days of development or revision, (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of development or revision, whichever is later, and (iii) to the Compliance Enforcement Authority or Applicable Governmental Authority when revised under D.A.11.4 within 90 calendar days of revision.

D.A.11.5.1. If a recipient of the CAP provides documented comments on the CAP, the responsible entity shall provide a documented response to that recipient within 90 calendar days of receipt of those comments.

D.A.M.11. Each responsible entity, as determined in Requirement R1, that concludes, through the supplemental GMD Vulnerability Assessment conducted in Requirement R8, that the responsible entity's System does not meet the performance requirements for the steady state planning supplemental GMD event contained in Table 1 shall have evidence such as dated electronic or hard copies of its CAP including timetable for implementing selected actions, as specified in Requirement R11. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records or postal receipts showing recipient and date, that it has revised its CAP if situations beyond the responsible entity's control prevent implementation of the CAP within the timetable specified. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has distributed its CAP or relevant information, if any, (i) to the responsible entity's Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), and functional entities referenced in the CAP within 90 calendar days of development or revision, (ii) to any functional entity that submits a written request and has a reliability-related need within 90 calendar days of receipt of such request or within 90 calendar days of development or revision, whichever is later as specified in Requirement R11, and (iii) to the Compliance Enforcement Authority or Applicable Governmental Authority when revised under D.A.11.4 within 90 calendar days of revision. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email notices or postal receipts showing recipient and date, that it has provided a documented response to comments received on its CAP within 90 calendar days of receipt of those comments, in accordance with Requirement R11.

E. Associated Documents

Attachment 1

Attachment 1-CAN

Version History

Version	Date	Action	Change Tracking
1	December 17, 2014	Adopted by the NERC Board of Trustees	New
2	November 9, 2017	Adopted by the NERC Board of Trustees	Revised to respond to directives in FERC Order No. 830.
2	November 25, 2018	FERC Order issued approving TPL-007-2. Docket No. RM18-8-000	
3	February 7, 2019	Adopted by the NERC Board of Trustees	Canadian Variance
4	February 6, 2020	Adopted by the NERC Board of Trustees	Revised to respond to directives in FERC Order. 851
4	March 19, 2020	FERC Order issued approving TPL-007-4. Docket No. RD20-3-000	

Attachment 1

Calculating Geoelectric Fields for the Benchmark and Supplemental GMD Events

The benchmark GMD event[1] defines the geoelectric field values used to compute GIC flows that are needed to conduct a benchmark GMD Vulnerability Assessment. It is composed of the following elements: (1) a reference peak geoelectric field amplitude of 8 V/km derived from statistical analysis of historical magnetometer data; (2) scaling factors to account for local geomagnetic latitude; (3) scaling factors to account for local earth conductivity; and (4) a reference geomagnetic field time series or waveform to facilitate time-domain analysis of GMD impact on equipment.

The supplemental GMD event is composed of similar elements as described above, except (1) the reference peak geoelectric field amplitude is 12 V/km over a localized area; and (2) the geomagnetic field time series or waveform includes a local enhancement in the waveform.[2]

The regional geoelectric field peak amplitude used in GMD Vulnerability Assessment, E_{peak}, can be obtained from the reference geoelectric field value of 8 V/km for the benchmark GMD event (1) or 12 V/km for the supplemental GMD event (2) using the following relationships:

$$E_{peak} = 8 \times \alpha \times \beta_b \ (V/km) \tag{1}$$

$$E_{peak} = 12 \times \alpha \times \beta_s \ (V/km) \tag{2}$$

where, α is the scaling factor to account for local geomagnetic latitude, and β is a scaling factor to account for the local earth conductivity structure. Subscripts *b* and *s* for the β scaling factor denote association with the benchmark or supplemental GMD events, respectively.

Scaling the Geomagnetic Field
The benchmark and supplemental GMD events are defined for geomagnetic latitude of 60° and must be scaled to account for regional differences based on geomagnetic latitude. Table 2 provides a scaling factor correlating peak geoelectric field to geomagnetic latitude. Alternatively, the scaling factor α is computed with the empirical expression:

$$\alpha = 0.001 \times e^{(0.115 \times L)} \tag{3}$$

where, L is the geomagnetic latitude in degrees and 0.1 ≤ α ≤ 1.

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[1] The Benchmark Geomagnetic Disturbance Event Description, May 2016 is available on the Related Information webpage for TPL-007-1: http://www.nerc.com/pa/Stand/TPL0071RD/Benchmark_clean_May12_complete.pdf.

[2] The extent of local enhancements is on the order of 100 km in North-South (latitude) direction but longer in East-West (longitude) direction. The local enhancement in the geomagnetic field occurs over the time period of 2-5 minutes. Additional information is available in the Supplemental Geomagnetic Disturbance Event Description, October 2017 white paper on the Project 2013-03 Geomagnetic Disturbance Mitigation project webpage: http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx.

For large planning areas that cover more than one scaling factor from Table 2, the GMD Vulnerability Assessment should be based on a peak geoelectric field that is:

- calculated by using the most conservative (largest) value for α; or

- calculated assuming a non-uniform or piecewise uniform geomagnetic field.

Table 2: Geomagnetic Field Scaling Factors for the Benchmark and Supplemental GMD Events	
Geomagnetic Latitude (Degrees)	Scaling Factor1 (α)
≤ 40	0.10
45	0.2
50	0.3
54	0.5
56	0.6
57	0.7
58	0.8
59	0.9
≥ 60	1.0

Scaling the Geoelectric Field

The benchmark GMD event is defined for the reference Quebec earth model described in Table 4. The peak geoelectric field, E_{peak}, used in a GMD Vulnerability Assessment may be obtained by either:

- Calculating the geoelectric field for the ground conductivity in the planning area and the reference geomagnetic field time series scaled according to geomagnetic latitude, using a procedure such as the plane wave method described in the NERC GMD Task Force GIC Application Guide;[3] or

- Using the earth conductivity scaling factor β from Table 3 that correlates to the ground conductivity map in Figure 1 or Figure 2. Along with the scaling factor α from equation (3) or Table 2, β is applied to the reference geoelectric field using equation (1 or 2, as applicable) to obtain the regional geoelectric field peak amplitude E_{peak} to be used in GMD Vulnerability Assessments. When a ground conductivity model is not available, the responsible entity should use the largest β factor of adjacent physiographic regions or a technically justified value.

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[3] Available at the NERC GMD Task Force project webpage: http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx.

The earth models used to calculate Table 3 for the United States were obtained from publicly available information published on the U. S. Geological Survey website.[4] The models used to calculate Table 3 for Canada were obtained from Natural Resources Canada (NRCan) and reflect the average structure for large regions. A planner can also use specific earth model(s) with documented justification and the reference geomagnetic field time series to calculate the β factor(s) as follows:

$$\beta_b = E/8 \text{ for the benchmark GMD event} \tag{4}$$

$$\beta_s = E/12 \text{ for the supplemental GMD} \tag{5}$$

where, *E* is the absolute value of peak geoelectric in V/km obtained from the technically justified earth model and the reference geomagnetic field time series.

For large planning areas that span more than one β scaling factor, the most conservative (largest) value for β may be used in determining the peak geoelectric field to obtain conservative results. Alternatively, a planner could perform analysis using a non-uniform or piecewise uniform geoelectric field.

Applying the Localized Peak Geoelectric Field in the Supplemental GMD Event
The peak geoelectric field of the supplemental GMD event occurs in a localized area.[5] Planners have flexibility to determine how to apply the localized peak geoelectric field over the planning area in performing GIC calculations. Examples of approaches are:

- Apply the peak geoelectric field (12 V/km scaled to the planning area) over the entire planning area;

- Apply a spatially limited (12 V/km scaled to the planning area) peak geoelectric field (e.g., 100 km in North-South latitude direction and 500 km in East-West longitude direction) over a portion(s) of the system, and apply the benchmark GMD event over the rest of the system; or

- Other methods to adjust the benchmark GMD event analysis to account for the localized geoelectric field enhancement of the supplemental GMD event.

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[4] Available at http://geomag.usgs.gov/conductivity/.
[5] See the Supplemental Geomagnetic Disturbance Description white paper located on the Project 2013-03 Geomagnetic Disturbance Mitigation project webpage: http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx.
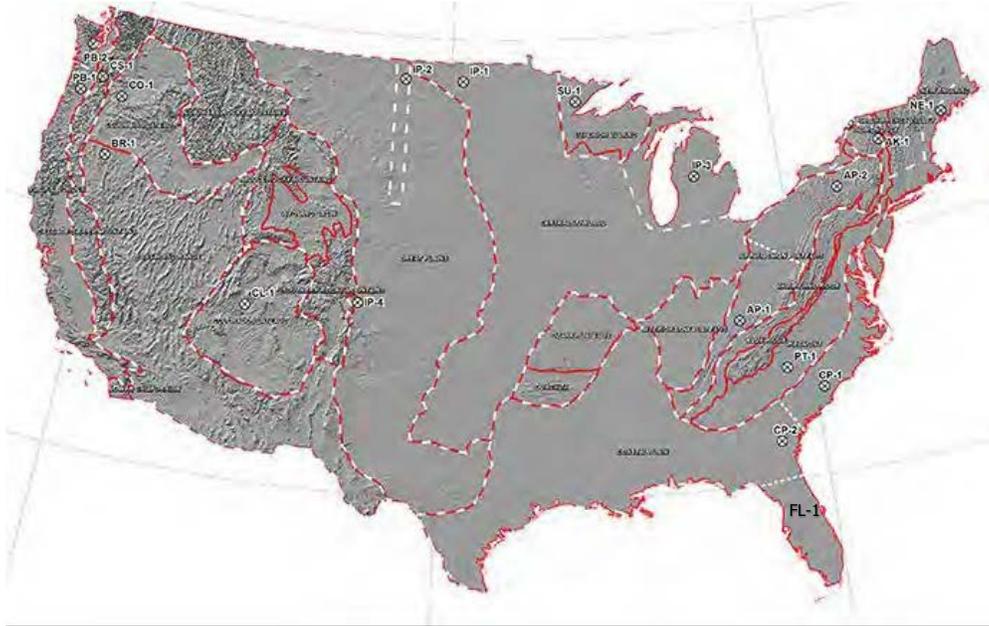
Figure 1: Physiographic Regions of the Continental United States[6]

Figure 2: Physiographic Regions of Canada

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[6] Additional map detail is available at the U.S. Geological Survey: http://geomag.usgs.gov/.

Table 3: Geoelectric Field Scaling Factors		
Earth model	**Scaling Factor Benchmark Event (β_b)**	**Scaling Factor Supplemental Event (β_s)**
AK1A	0.56	0.51
AK1B	0.56	0.51
AP1	0.33	0.30
AP2	0.82	0.78
BR1	0.22	0.22
CL1	0.76	0.73
CO1	0.27	0.25
CP1	0.81	0.77
CP2	0.95	0.86
FL1	0.76	0.73
CS1	0.41	0.37
IP1	0.94	0.90
IP2	0.28	0.25
IP3	0.93	0.90
IP4	0.41	0.35
NE1	0.81	0.77
PB1	0.62	0.55
PB2	0.46	0.39
PT1	1.17	1.19
SL1	0.53	0.49
SU1	0.93	0.90
BOU	0.28	0.24
FBK	0.56	0.56
PRU	0.21	0.22
BC	0.67	0.62
PRAIRIES	0.96	0.88
SHIELD	1.0	1.0
ATLANTIC	0.79	0.76

Scaling factors in Table 3 are dependent upon the frequency content of the reference storm. Consequently, the benchmark GMD event and the supplemental GMD event may produce different scaling factors for a given earth model.

Table 4: Reference Earth Model (Quebec)	
Layer Thickness (km)	**Resistivity (Ω-m)**
15	20,000
10	200
125	1,000
200	100
∞	3

Reference Geomagnetic Field Time Series or Waveform for the Benchmark GMD Event[7]

The geomagnetic field measurement record of the March 13-14 1989 GMD event, measured at the NRCan Ottawa geomagnetic observatory, is the basis for the reference geomagnetic field waveform to be used to calculate the GIC time series, GIC(t), required for transformer thermal impact assessment.

The geomagnetic latitude of the Ottawa geomagnetic observatory is 55°; therefore, the amplitudes of the geomagnetic field measurement data were scaled up to the 60° reference geomagnetic latitude (see Figure 3) such that the resulting peak geoelectric field amplitude computed using the reference earth model was 8 V/km (see Figures 4 and 5). The sampling rate for the geomagnetic field waveform is 10 seconds.[8] To use this geoelectric field time series when a different earth model is applicable, it should be scaled with the appropriate benchmark conductivity scaling factor β_b.

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[7] Refer to the Benchmark Geomagnetic Disturbance Event Description white paper for details on the determination of the reference geomagnetic field waveform: http://www.nerc.com/pa/stand/Pages/TPL0071RI.aspx.

[8] The data file of the benchmark geomagnetic field waveform is available on the Related Information webpage for TPL-007-1: http://www.nerc.com/pa/stand/Pages/TPL0071RI.aspx.
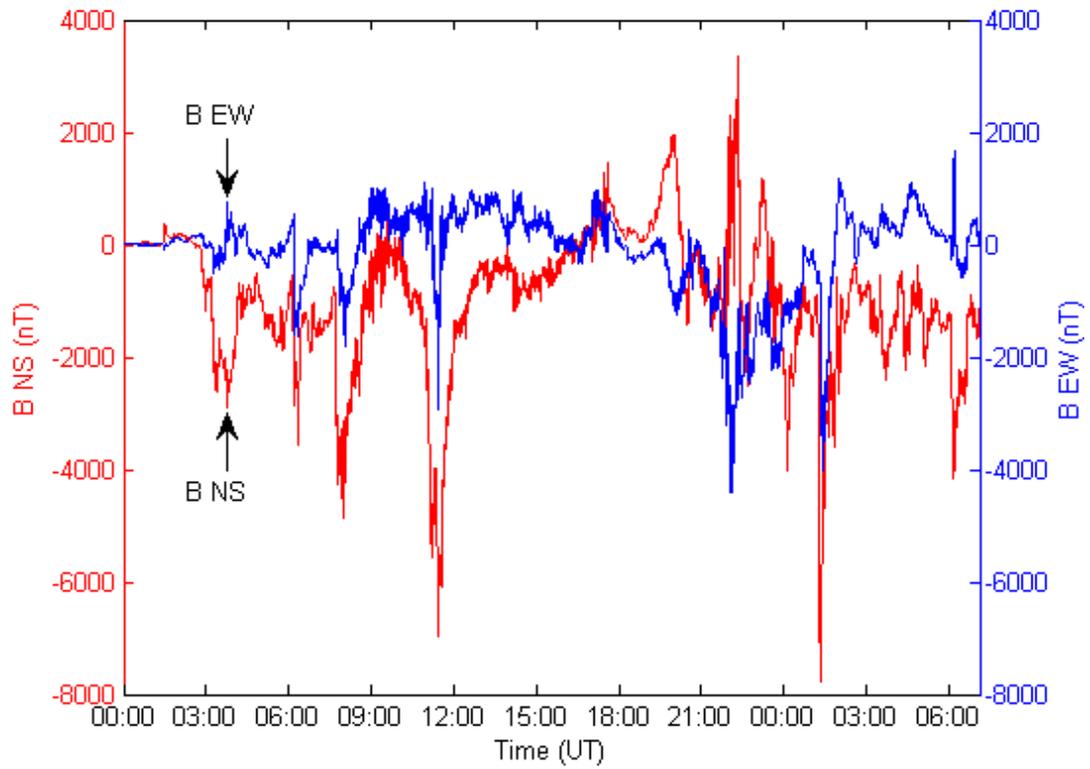
Figure 3: Benchmark Geomagnetic Field Waveform
Red B_n (Northward), Blue B_e (Eastward)
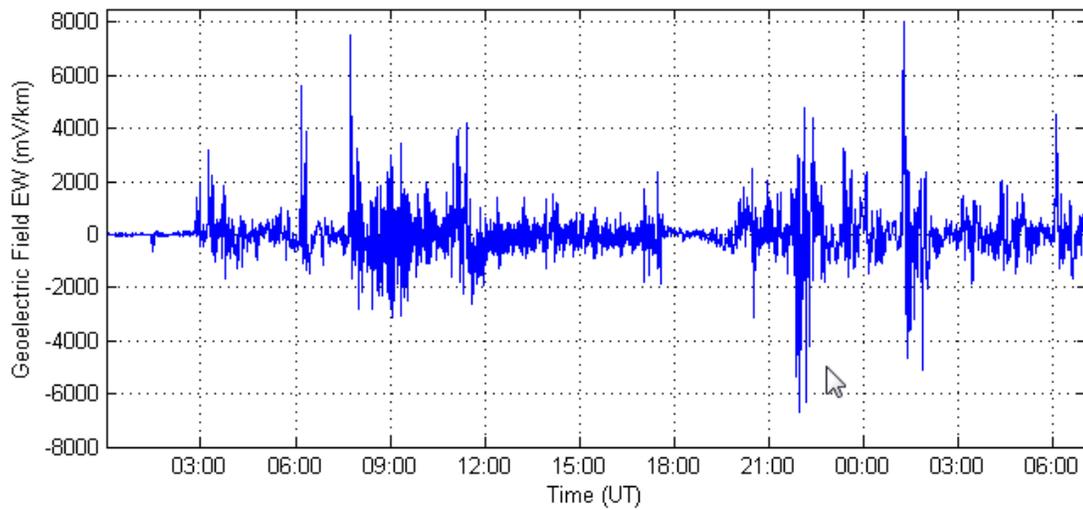
Figure 4: Benchmark Geoelectric Field Waveform
E_E (Eastward)
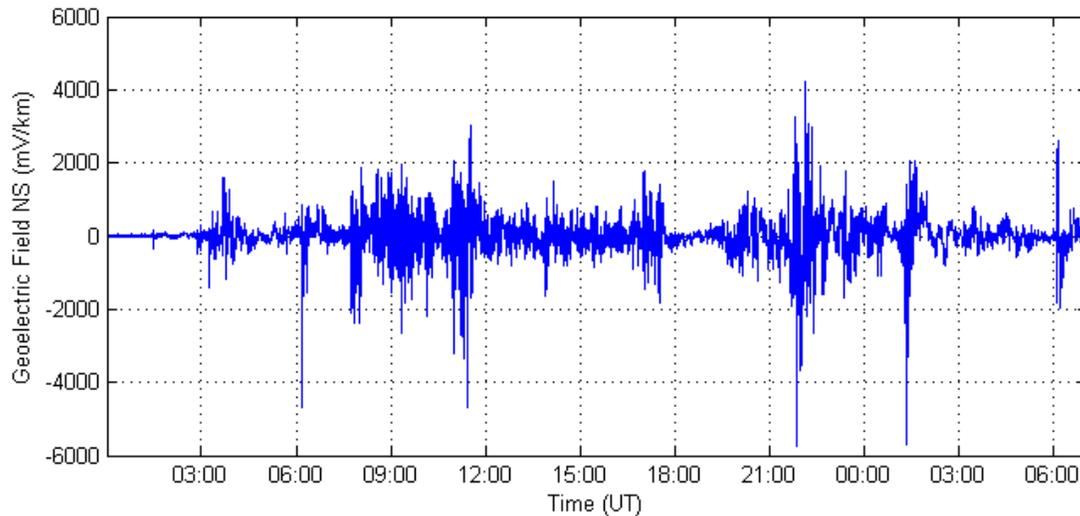
Figure 5: Benchmark Geoelectric Field Waveform
E_N (Northward)

Reference Geomagnetic Field Time Series or Waveform for the Supplemental GMD Event[9]

The geomagnetic field measurement record of the March 13-14, 1989 GMD event, measured at the NRCan Ottawa geomagnetic observatory, is the basis for the reference geomagnetic field waveform to be used to calculate the GIC time series, GIC(t), required for transformer thermal impact assessment for the supplemental GMD event. The supplemental GMD event waveform differs from the benchmark GMD event waveform in that the supplemental GMD event waveform has a local enhancement.

The geomagnetic latitude of the Ottawa geomagnetic observatory is 55°; therefore, the amplitudes of the geomagnetic field measurement data were scaled up to the 60° reference geomagnetic latitude (see Figure 6) such that the resulting peak geoelectric field amplitude computed using the reference earth model was 12 V/km (see Figure7). The sampling rate for the geomagnetic field waveform is 10 seconds.[10] To use this geoelectric field time series when a different earth model is applicable, it should be scaled with the appropriate supplemental conductivity scaling factor β_s.

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[9] Refer to the Supplemental Geomagnetic Disturbance Event Description white paper for details on the determination of the reference geomagnetic field waveform: http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx.

[10] The data file of the benchmark geomagnetic field waveform is available on the NERC GMD Task Force project webpage: http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx.
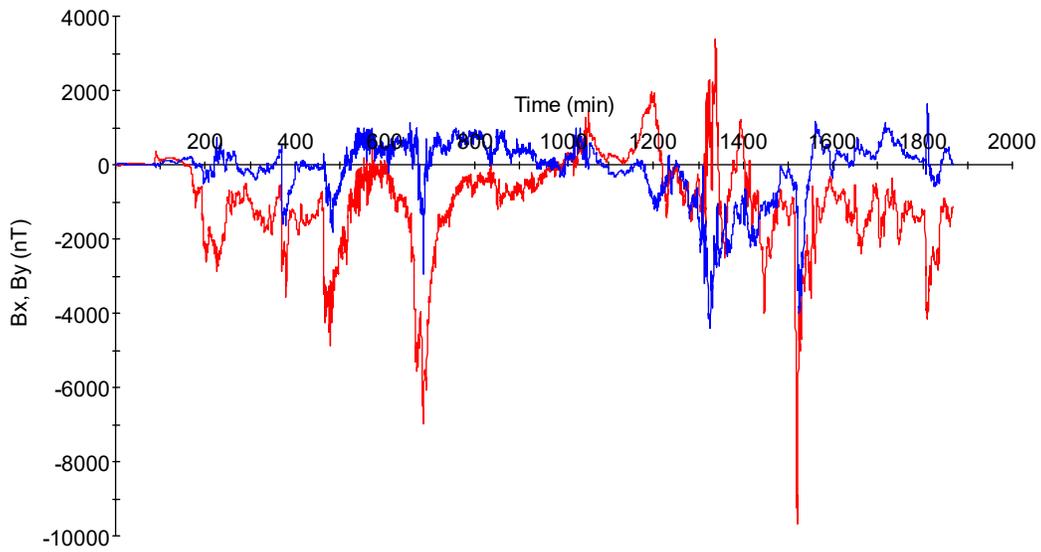
**Figure 6: Supplemental Geomagnetic Field Waveform
Red B_N (Northward), Blue B_E (Eastward)**
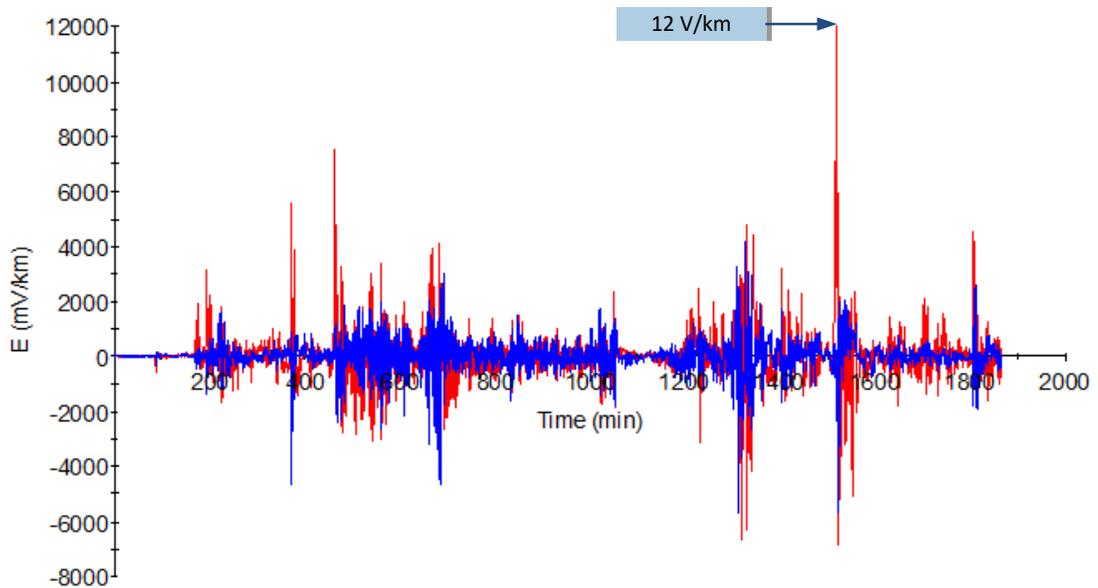
**Figure 7: Supplemental Geoelectric Field Waveform
Blue E_N (Northward), Red E_E (Eastward)**

Attachment 1-CAN

Attachment 1-CAN provides an alternative that a Canadian entity may use in lieu of the benchmark or supplemental GMD event(s) defined in Attachment 1 for performing GMD Vulnerability Assessment(s).

A Canadian entity may use the provisions of Attachment 1-CAN if it has regionally specific information that provides a technically justified means to re-define a 1-in-100 year GMD planning event(s) within its planning area.

Information for the Alternative Methodology

GMD Vulnerability Assessment(s) require the use of geophysical and engineering models. Canadian-specific data is available and growing. Ongoing research allows for more accurate characterization of regional parameters used in these models. Such Canadian-specific data includes geomagnetic field, earth conductivity, and geomagnetically induced current measurements that can be used for modeling and simulation validation.

Information used to calculate geoelectric fields for the benchmark and supplemental GMD events shall be clearly documented and technically justified. For example, the factors involved in the calculation of geoelectric fields are geomagnetic field variations and an earth transfer function(s).[1] Technically justified information used in modelling geomagnetic field variations may include: technical documents produced by governmental entities such as Natural Resources Canada; technical papers published in peer-reviewed journals; and data sets gathered using sound scientific principles. An earth transfer function may rely on magnetotelluric measurements or earth conductivity models.

Modeling assumptions shall also be clearly documented and technically justified. An entity may use sensitivity analysis to identify how the assumptions affect the results.

A simplified model may be used to perform a GMD Vulnerability Assessment(s), as long as the model is more conservative than a more detailed model.

When interpreting assessment results, the entity shall consider the maturity of the modeling, toolset, and techniques applied.

Geomagnetic Disturbance Planning Events

The 1-in-100 year planning event shall be based on regionally specific data and technically justifiable statistical analyses (e.g., extreme value theory) and applied to the benchmark and supplemental GMD Vulnerability Assessment(s).

For the benchmark GMD Vulnerability Assessment(s), an entity shall consider the large-scale spatial structure of the GMD event. For the supplemental GMD Vulnerability Assessment(s), an

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[1] The "earth transfer function" is the relationship between the electric fields and magnetic field variations at the surface of the earth.

entity shall consider the small-scale spatial structure of the GMD event (e.g., using magnetometer measurements or realistic electrojet calculations).

Exhibit B

519-2022 - IEEE Standard for Harmonic Control in Electric Power Systems

Publisher: IEEE   Cite This   📄 PDF

🕐 Most Recent   **Status: Active - Approved**   ≡ Versions   📄 Amendments Available

211
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Papers

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Abstract

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Abstract:
Goals for the design of electrical systems that include both linear and nonlinear loads are established in this standard. The voltage and current waveforms that may exist throughout the system are described, and waveform distortion goals for the system designer are established. The interface between sources and loads is described as the point of common coupling and observance of the design goals will reduce interference between electrical equipment. This standard addresses steady-state limitations. Transient conditions exceeding these limitations may be encountered. This document sets the quality of power that is to be provided at the point of common coupling. This document does not cover the effects of radio-frequency interference; however, guidance is offered for wired telephone systems.

Scope:
This standard establishes goals for the design of electrical systems that include both linear and nonlinear loads. The voltage and current waveforms that may exist throughout the system are described, and waveform distortion goals for the system designer are established. The interface between sources and loads is described as the point of common coupling and observance of the design goals will reduce interference between electrical equipment. The voltage and current distortion limits in this standard shall apply at the user point of common coupling (PCC) to overall installation containing harmonic producing loads (nonlinear equipment). Users are directed to other applicable standards such as IEEE Std 1547 or IEEE Std 2800 for current distortion limits of inverter-based resources (IBR) installations. When no other applicable standard exists, users shall continue to use footnote "c" under Table 2 through Table 4 in this standard for IBR connected to transmission systems.

Purpose:
This standard is to be used for guidance in the design of power systems with nonlinear loads. The limits set are for steady state operating conditions. In any case, the limit values given in this document should not be considered binding in all cases. Some conservatism is present that may not be necessary in all cases. This standard shall be applied at a PCC between system owners or operators and users in the power system. The limits in this standard are intended for application at a PCC between the system owner or operator and a user, where the PCC is usually taken as the point in the power system closest to the user where the system owner or operator could offer service to another user. Frequently for service to industrial users (i.e., manufacturing plants) via a dedicated service transformer, the PCC is at the HV side of the transformer. For commercial users (office parks, shopping malls, etc.) supplied through a common service transformer, the PCC is commonly at the LV side of the service transformer.

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Exhibit C

"Physical Characteristics of HEMP Waveform Benchmarks for Use in Assessing Susceptibilities of the Power Grid, Electrical Infrastructures, and Other Critical Infrastructure to HEMP Insults" U.S. Department of Energy. January 11, 2021.

Department of Energy

DATE: January 11, 2021

FOR: NATIONAL SECURITY COUNCIL RECORDS

FROM: Secretary of Energy Dan Brouillette

SUBJECT: Physical Characteristics of HEMP Waveform Benchmarks for Use in
           Assessing Susceptibilities of the Power Grid, Electrical Infrastructures, and
           Other Critical Infrastructure to HEMP Insults

This memo is in response to the *Summary of Conclusions for the December 21, 2020
PSG Meeting on Benchmarks for Electromagnetic Pulses (EMP).*

This memo provides nuclear high-altitude electromagnetic pulse (HEMP) E1, E2 and E3
waveform recommendations for use by U.S. Government Agencies, industry, and other
risk-holders in assessing potential HEMP susceptibilities for non-Department of Defense
(DOD) Government agency and commercial sector specific electrical systems and other
networked infrastructures across the sixteen critical infrastructure sectors. The following
guidance is intended to fulfill Section 6 (b) (iii) of Presidential Executive Order 13865,
March 26, 2019 on Coordinating National Resilience to Electromagnetic Pulses.

These waveforms are not hardening standards and do not specify the level of risk critical
infrastructure faces from HEMP. The waveforms are representative of, and include
uncertainties to account for, the threat from HEMP over the planned lifecycle of critical
infrastructure investments (30-50 years). This memo is intended to be the first step in a
long conversation with civilian stakeholders to begin to understand the threat,
consequence, and risk associated with EMPs and how to address the risks.

These waveforms are intended to inform testing activities called for in EO 13865,
including 6(b)(i), 6(b)(ii), 6(c)(i), and 6(c)(ii). Once testing is completed by DOD, the
Department of Energy (DOE), the Department of Homeland Security (DHS), and others,
the results will inform the DHS completion of an EMP risk assessment (EO 13865
5(f)(vii)). Once testing and the risk assessment are completed, DHS, DOD, and DOE
will work to strengthen critical infrastructure, where necessary, to include the
development of standards for protecting existing and new infrastructure. The
development of standards will be done in consultation with the heads of other appropriate
agencies and with the private sector as appropriate.

The National Security Council recommends that U.S. electrical systems and other critical infrastructure elements can be assessed for disruption and damage susceptibility up to the benchmark HEMP waveforms (described below) characterized by peak electric field strengths of 50 kV/m for E1, 100 V/m for E2, 80 V/km for E3a (blast), and 50 V/km for E3b (heave), respectively. The E1, E2, and E3 benchmark waveforms were developed using available information. DOD's benchmark waveforms are detailed in Appendix A.

Testing at electric field strengths up to the peak values will inform owners, operators, and risk holders of the aforementioned electrical systems and networked infrastructures on the operational margins under HEMP stress levels that exceed DOE's currently assessed threat levels by a factor of 2 due to predictive modeling uncertainties and potential excursions in HEMP environment levels. However, DOD recommends that the benchmark waveforms provided be used as the basis for susceptibility testing, vulnerability assessments, modeling, and simulation to understand where disruptions and damage could occur from HEMP insults. These results will enable risk-informed decisions to be made at a later date on what to protect (based on results from planned tests and assessments) and to what level of protection.

The recommended E1, E2, and E3 HEMP environment benchmark waveforms will be updated as necessary, based on further developments in our understanding of HEMP generation and modeling and simulation phenomenology.

ATTACHMENTS:
1. APPENDIX A: HEMP waveform benchmarks
2. APPENDIX B: Using the HEMP Benchmark Waveforms for Susceptibility Assessments
3. APPENDIX C: References

APPENDIX A

HEMP Waveform Benchmarks
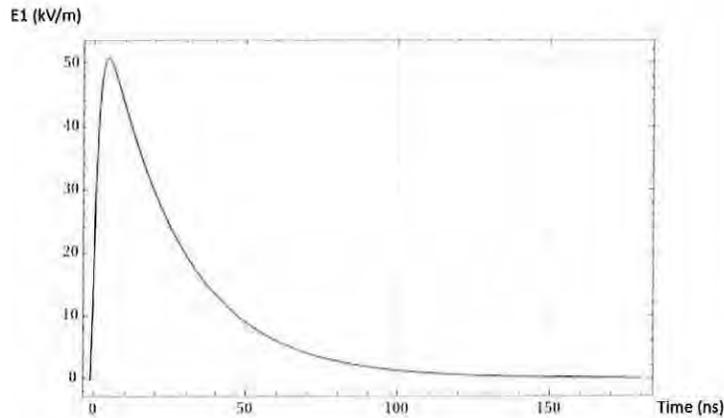
E1 Waveform

The early-time (E1) HEMP field waveform is given in the equation below as:

$$E1(t) = E_0 \cdot k(e^{-at} - e^{-bt}), \tag{1}$$

For time, $t > 0$, in seconds; and where the constants in the equation are given by $E_0 = 50 \ kV/m, k = 1.3, a = 4 \times 10^7 s^{-1}, b = 6 \times 10^8 s^{-1}$.

This E1 waveform is the previously published IEC-61000-2-9 E1 waveform and is shown in figure 1 below.[1] There are no previously established U.S. benchmark waveforms for assessing susceptibilities of U.S. national critical infrastructures or the U.S. electric power grid to HEMP insults.

Use of the HEMP E1 incident waveform, as provided in figure 1, is recommended for evaluating the susceptibility of U.S. national critical infrastructures and the U.S. power grid, based on interagency policy discussions regarding present and future uncertainties.

$$E1(t) = E_0 \cdot k(e^{-at} - e^{-bt})$$

	E_0	k	$a \ (s^{-1})$	b (s^{-1})
Level	$50 \ kV/m$	1.3	4×10^7	6×10^8

Figure 1. E1 benchmark waveform. E1 waveform equation coefficients are provided below the waveform.

The current Military Standard (MIL STD) for defense equipment as of December 2020 is 2169C. Those values will be considered for discussion with stakeholders when/if deemed appropriate.

Table 1. Historical comparison of E1 waveforms[1] (ranging from 50 to 60 kV/m peak field strength)

Parameter	Bell Labs (1960s) DEXP	Baum (1992) DEXP	Baum (1992) QEXP	IEC-77C (1993) DEXP	Leuthauser (1994) QEXP	VG95371-10 (1995) DEXP	IEC 6100-2-9 (1996) DEXP
$t_{10\%-90\%}$	4.6 ns	2.5 ns	2.4 ns	2.5 ns	1.9 ns	0.9 ns	2.5 ns
Peak Field E_0	50 kV/m	50 kV/m	50 kV/m	50 kV/m	60 kV/m	65 kV/m	50 kV/m
FWHM	184 ns	~23 ns	~24 ns	23 ns	23.8 ns	24.1 ns	23 ns
constant	1.05	1.3	1.114	1.3	1.08	1.085	1.3
α (1/sec)	4×10^6	4×10^7	1.6×10^9	4×10^7	2.20×10^9	3.22×10^7	4×10^7
β (1/sec)	4.76×10^8	6×10^8	3.7×10^7	6×10^8	3.24×10^7	2.07×10^9	6×10^8
Energy Density (J/m^2)	0.891	0.114	0.107	0.114	0.167	0.196	0.114

E2 Waveform

The intermediate-time (E2) HEMP field waveform is given as:

$$E2\ (t) = E_0 \cdot (e^{-at} - e^{-bt})\ ,$$

For time, t > 0, in seconds; and where the constants in the equation above are given by $E_0 = 100$ *V/m*, $a = 1000\ s^{-1}$, and $b = 6 \times 10^8\ s^{-1}$.

The E2 waveform is characterized by an amplitude of 10 V/m to 100 V/m for times between approximately 0.01 μs and 1 ms.[i] The orientation of the E2 electric field is predominately orthogonal to Earth's surface.
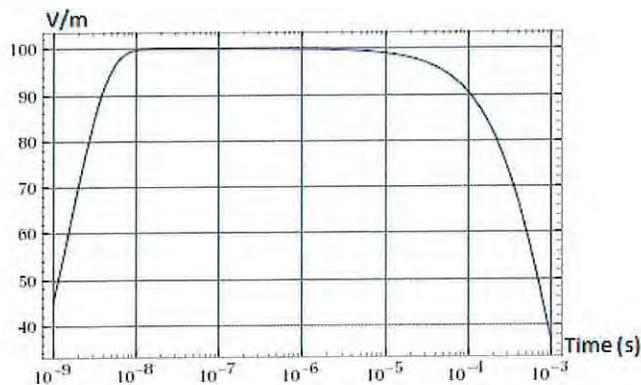

Figure 2. Recommended E2 benchmark waveform.

The current Military Standard (MIL STD) for defense equipment as of December 2020 is 2169C. Those values will be considered for discussion with stakeholders when/if deemed appropriate.

E3 Waveforms

The late-time E3 HEMP waveform is comprised of two separate waveforms, summed together, that are defined by differing late-time HEMP phenomenology considerations, and are represented by this equation

$$E_3(t) = E_{3a}(t) + E_{3b}(t)$$

These waveforms are defined as the E3a (blast waveform) and E3b (heave waveform), respectively, and are defined below. The E3a and E3b waveforms can be separated in time by several seconds, and the peak field strengths fall at different locations on the ground[ii,iii]

E3a – blast Waveform

The late-time E_{3a} (blast) HEMP waveform (see figure 3) is based on earlier work by Oak Ridge National Laboratory (ORNL) and the EMP Commission,[iv,v,vi] and is given by the following curve-fit based equation in units of V/km,

$$E_{3a}(t) = \alpha e^{-t/\beta}(\gamma t - \delta t^2)$$

for t > 0, in seconds; and where the constants in the equation are given by,

$$\alpha = 9.5,$$
$$\beta = 1.4,$$
$$\gamma = 26, \text{ and}$$
$$\delta = 8.9$$

The E_{3a} (blast) waveform applies for $t > 0$, where $E_{max} = 80$ V/km, and a ground conductivity of 10^{-3} S/m that is suitable for a mid-latitude Continental United State (CONUS) location of 40° N. The peak E3a field strength can vary depending on the latitude under consideration and the local ground conductivity values, and further guidance on how to account for these effects is provided below.
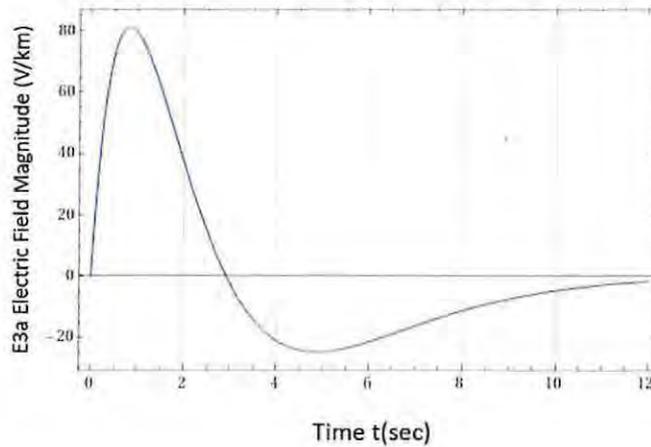
$E_{3a}(t) = \alpha e^{-t/\beta}(\gamma t - \delta t^2)$, in units of V/km for t (secs)

	α	β	$\gamma\ (s^{-1})$	$\delta\ (s^{-2})$
Level	9.5	1.4	26	8.9

Figure 3. E3a–blast benchmark waveforms to be used for susceptibility testing. E3a–blast waveform equation constant coefficients are provided below the waveforms, in the table above.

The current Military Standard (MIL STD) for defense equipment as of December 2020 is 2169C. Those values will be considered for discussion with stakeholders when/if deemed appropriate.

E3b – heave Waveform

The late-time E_{3b} (heave) HEMP waveform is given by the following curve-fit based equation in units of V/km,

$$E_{3b}(t) = -\alpha t^2 e^{-t/\gamma} \frac{\beta^3 t - 3\beta^3 \gamma + t^4}{\gamma(\beta^3 + t^3)^2}$$

For time, t > 0, in seconds, and where the constants in the equation are given by,
$$\alpha = 13 \times 10^5,$$
$$\beta = 200, \text{ and}$$
$$\gamma = 20$$

The E_{3b} (heave) waveform applies for $t > 0$, a ground conductivity of 10^{-3} S/m and a mid-latitude CONUS location of 40° N.[vii] This recommended E_{3b} waveform represents a change relative to the previous international waveform;[viii] and it applies for $t > 0$, where $E_{max} = 50$ V/km.
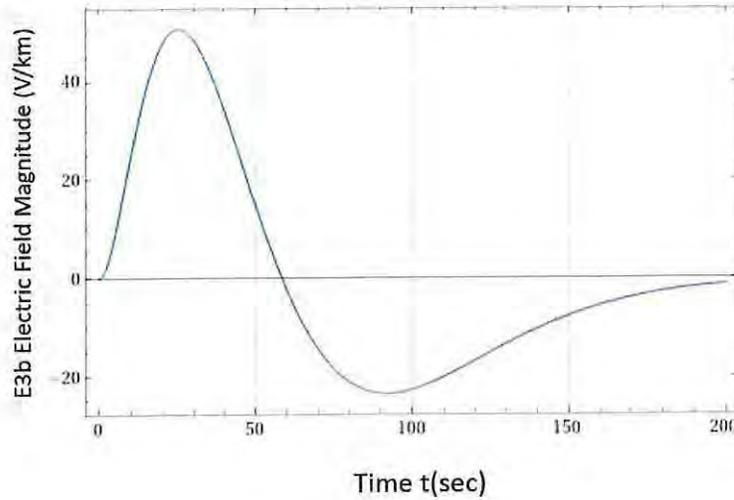
$$E_{3b}(t) = -\alpha t^2 e^{-t/\gamma} \frac{\beta^3 t - 3\beta^3 \gamma + t^4}{\gamma(\beta^3 + t^3)^2} \text{, in units of V/km for t (secs)}$$

	α	β	γ
Level	13×10^5	200	20

Figure 4. E3b benchmark waveform to be used for susceptibility testing. E3b (heave) waveform equation coefficients are provided below the waveform, in the table above.

The current Military Standard (MIL STD) for defense equipment as of December 2020 is 2169C. Those values will be considered for discussion with stakeholders when/if deemed appropriate.

APPENDIX B

Using the HEMP Benchmark Waveforms for Susceptibility Assessments

Existing HEMP testing protocols may be used to evaluate susceptibilities for sector or enterprise-specific electronics and networked infrastructure elements to the E1, E2, and E3 benchmark HEMP waveforms. Additional information on existing HEMP waveform testing approaches can be found in the HEMP IEC 61000-series[ix,x] and DOD Mil-Standards[xi,xii,xiii] and Handbooks[xiv] to assess HEMP resilience.

The National Security Council recommends infrastructure owners, operators, and risk holders use suitable HEMP coupling models and test data, as appropriate, to determine component and system susceptibilities attributable to the currents and voltages induced within their infrastructure elements following exposure to the recommended incident E1, E2, and E3 HEMP benchmark waveforms. For E3 coupling assessments, infrastructure owners and operators should incorporate local ground conductivity values, such as those provided by current and future magnetotelluric surveys,[xv,xvi] and account for latitude effects on the induced current and voltage loading on hardware connected to long conductive lines.

DOE recommends that select electronics and energy infrastructure element hardware be tested starting at low peak field strength levels, for example equivalent to 1 kV/m, and then at increasing values to determine the levels at where disruption and damage occur.

Disruption and damage effects observed during testing at each insult level should be evaluated and documented. For awareness, DOE, DOD Defense Threat Reduction Agency, and other organizations have archives of HEMP test data and assessment reports of various electrical and energy infrastructure elements that can be made available as appropriate, and in addition some relevant information can also be found in open publications. For each of the selected test levels, the local effects and results observed at the component level should be documented and then integrated into the overall response of the networked infrastructure through modeling- and simulation-based assessments to determine the predicted system-wide response and effect(s). These modeling efforts, vulnerability and consequence assessments, and associated test data should be safeguarded and shared with U.S. Government agencies, including the Department of Homeland Security, or their delegates, as appropriate. Each vulnerability evaluation and hardening decision will likely be unique to that particular infrastructure element and involve the relevant owners, operators and risk holders.

The U.S. government will provide, by early 2021, general technical guidance to National Laboratories and other expert organizations on how energy sector-specific and other owners, operators, and risk holders can conduct HEMP susceptibility testing and assessments, and how to safeguard and share those data and assessments with relevant U.S Government Agencies.

APPENDIX C: References

[i] IEC Ref. No. EN 61000-2-9, https://webstore.iec.ch/publication/4141

[ii] Dyal, Palmer (2006). "Particle and field measurements of the Starfish diamagnetic cavity." Journal of Geophysical Research: Space Physics 111.A12.

[iii] Meta-R-321, The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid, January 2010.

[iv] ORNL/Sub/90-SG828/1, Magnetohydrodynamic Electromagnetic Pulse (MHD-EMP) Interaction with Power Transmission And Distribution Systems, February 1992.

[v] EMP Commission, Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures, July 2017.

[vi] Dyal, Palmer (2006). "Particle and field measurements of the Starfish diamagnetic cavity." Journal of Geophysical Research: Space Physics 111.A12.

[vii] IEC Ref. No. EN 61000-2-10 Ed. 1.0 (1998-11): Electromagnetic Compatibility (EMC) – Part 2-10: Environment – Description of HEMP Environment – Radiated disturbance, Basic EMC publication.

[viii] IEC Ref. No. EN 61000-2-10 Ed. 1.0 (1998-11): Electromagnetic Compatibility (EMC) – Part 2-10: Environment – Description of HEMP Environment – Radiated disturbance, Basic EMC publication.

[ix] IEC Ref. No. EN 61000-2-9; Electromagnetic compatibility (EMC) - Part 2: Environment - Section 9: Description of HEMP environment - Radiated disturbance; 1996.

[x] IEC Ref. No. EN 61000-2-10; Electromagnetic compatibility (EMC) –Part 2-10: Environment – Description of HEMP environment – Conducted disturbance; 1998.

[xi] Mil-Std 188-125

[xii] Mil-Std 3023

[xiii] Mil-Std 464C, ELECTROMAGNETIC ENVIRONMENTAL EFFECTS REQUIREMENTS FOR SYSTEMS, 1 Dec 2010.

[xiv] Mil-Hdbk-423

[xv] USGS; Report; published March 5, 2019; New U.S. Geological Survey Report Assesses Risk of Once-Per-Century Geomagnetic Superstorm to the Northeastern United States; at https://www.usgs.gov/news/new-us-geological-survey-report-assesses-risk-once-century-geomagnetic-superstorm-northeastern; site accessed May 5, 2020.

[xvi] Oregon State University; Paper presented at Space Weather Workshop, Boulder CO 3-April-2019; Integrating space weather and ground-based magnetotelluric data with powerflow solutions for real-time assessment of risk to the power grid; at https://www.swpc.noaa.gov/sites/default/files/images/u59/02%20Adam%20Schultz%20Official.pdf; site accessed May 5, 2020.

Exhibit D

"Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures." Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. July 2017.

Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures

Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures

July 2017

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

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

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

The Commission completed its information-gathering in June 2017. The report was cleared for open publication by the DoD Office of Prepublication and Security Review on April 9, 2018.

This report is unclassified and cleared for public release.

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ACRONYMS AND ABBREVIATIONS

B	magnetic field
CONUS	continental United States
DoD	Department of Defense
E	electric field
EMP	electromagnetic pulse
EPRI	Electric Power Research Institute
FERC	Federal Energy Regulatory Commission
GMD	geomagnetic disturbance
HEMP	high-altitude electromagnetic pulse
HOB	height of burst
km	kilometer
m	meter
MHD	magnetohydrodynamic
min	minute
NERC	North American Electric Reliability Corporation
nT	nanotesla
S/m	siemens/m
UV	ultraviolet
V	Volt

PREFACE

This EMP Commission Report, utilizing unclassified data from Soviet-era nuclear tests, establishes that recent estimates by the Electric Power Research Institute (EPRI) and others that the low-frequency component of nuclear high-altitude EMP (E3 HEMP) are too low by at least a factor of 3. Moreover, this assessment disproves another claim--often made by the U.S. Federal Energy Regulatory Commission (FERC), the North American Electric Reliability Corporation (NERC), EPRI and others—that the FERC-NERC Standard for solar storm protection against geo-magnetic disturbances (8 volts/kilometer, V/km) will also protect against nuclear E3 HEMP. A realistic unclassified peak level for E3 HEMP would be 85 V/km for CONUS as described in this report. New studies by EPRI and others are unnecessary since the Department of Defense has invested decades producing accurate assessments of the EMP threat environment and of technologies and techniques for cost-effective protection against EMP. The best solution is for DoD to share this information with industry to support near-term protection of electric grids and other national critical infrastructures that are vital both for DoD to perform its missions and for the survival of the American people.

EXECUTIVE SUMMARY

As described in this report, there is a need to have bounding information for the late-time (E3) high-altitude electromagnetic pulse (HEMP) threat waveform and a ground pattern to study the impact of these types of electromagnetic fields on long lines associated with the critical infrastructures. It is important that this waveform be readily available and useful for those working in the commercial sectors.

While the military has developed worst-case HEMP waveforms (E1, E2, and E3) for its purposes, these are not available for commercial use. Therefore, in this report openly available E3 HEMP measurements are evaluated from two high-altitude nuclear tests performed by the Soviet Union in 1962. Using these data waveforms and an understanding of the scaling relationships for the E3 HEMP heave phenomenon, bounding waveforms for commercial applications were developed.

Since the measured quantities during these tests were the magnetic fields, it is possible to compute the electric fields assuming ground conductivity profiles that produce significant levels. There are other profiles that would compute even higher electric fields, but some of these profiles do not cover a very large area of the Earth.

After computing the electric fields using the Soviet measurements, the results were scaled to account for the fact that their measurement locations were not at the optimum points on the ground to capture the maximum peak fields. Through this process, it was determined that the scaled maximum peak E3 HEMP heave field would have been 66 volts per kilometer (V/km) for the magnetic latitude of the Soviet tests.

As the E3 HEMP heave field also increases for burst points closer to the geomagnetic equator, the measured results were also evaluated for this parameter. This scaling increases the maximum peak electric field up to 85 V/km for locations in the southern part of the continental U.S., and 102 V/km for locations nearer to the geomagnetic equator, as in Hawaii. The levels in Alaska would be lower at an estimated peak value of 38 V/km (see Table 5 for information dealing with this scaling process).

It is noted that this report does not claim that the values provided here are absolute worst-case field levels, but rather these peak levels are estimated based directly on measurements made during Soviet high-altitude nuclear testing.

1   INTRODUCTION

Over many years beginning in the 1980s, the U.S. has worked to establish the peak field levels, ground patterns of the heave portion of the late-time E3 HEMP fields as shown in Figure 1, and from these to build useful models.[1,2] In the summer of 1994, Soviet scientists attending the European Electromagnetics (EUROEM) Symposium in Bordeaux, France, presented several papers indicating their understanding of the different types of EMP including the high-altitude electromagnetic pulse (HEMP). One of the most interesting developments of that conference was that these presentations summarized the Soviet high-altitude electromagnetic test results and indicated that the most important aspects of the effects they observed were caused by the "long tail" of the HEMP.[3] In later publications, they indicated that the long tail referred to the late-time HEMP, or the E3 HEMP magnetohydrodynamic (MHD)-EMP heave signal, and later provided detailed technical information indicating that the failure of one long-haul communications line was due to this portion of the HEMP.[4] Three other references dealing with E3 HEMP (MHD-EMP) were published by Soviet scientists in this time frame presumably due to their interest in understanding the failures of commercial long line systems during their 1962 high-altitude nuclear testing program over Kazakhstan.[5,6,7]

Later in the early 2000s, Soviet scientists provided the EMP Commission with a memo that illustrated their magnetic field measurements of the E3 HEMP heave signals at three locations during two of their high-altitude nuclear tests over Kazakhstan in 1962.[8] Because the Soviets tested over land instead of over ocean, as did the U.S., several long line systems were affected by the E3 HEMP fields. In addition, measurements of the magnetic fields were made at several locations on the ground at various ranges from the surface zero (the point directly underneath the high-altitude burst).

1   J. Gilbert, J. Kappenman, W. Radasky and E. Savage, "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid," Meta R-321, January 2010.
2   J.L. Gilbert, W.A. Radasky, K.S. Smith, K. Mallen, M.L. Sloan, J.R. Thompson, C.S. Kueny and E. Savage, "HEMPTAPS/HEMP-PC Audit Report." Meta R-131, December 1999; DTRA-TR-00-1, April 2002.
3   V.M. Loborev, "Up to Date State of the NEMP Problems and Topical Research Directions," Proceedings of the European Electromagnetics International Symposium -- EUROEM 94, June 1994, pp. 15-21.
4   V.N. Greetsai, A.H. Kozlovsky, V.M. Kuvshinnikov, V.M. Loborev, Y.V. Parfenov, O.A. Tarasov and L.N. Zdoukhov, "Response of Long Lines to Nuclear High-Altitude Nuclear Pulse (HEMP)," IEEE Transactions on EMC, Vol. 40, Issue 4, 1998, pp. 348-354.
5   V.N. Greetsai, V.M. Kondratiev, and E.L. Stupitsky, "Numerical Modelling of the Processes of High-Altitude Nuclear Explosion MDH-EMP Formation and Propagation," Roma International Symposium on EMC, September 1996, pp. 769-771.
6   "The Physics of Nuclear Explosions," Ministry of Defense of the Russian Federation, Central Institute of Physics and Technology, Volumes 1 and 2, ISBN 5-02-015124-6, 1997. MHD-EMP topics are found in Sections 13.5 and 13.6.3.
7   V.M. Kondratiev and V.V. Sokovikh, "Redetermination of MHD-EMP Amplitude Characteristics and Spatial Distribution on the Ground Surface," Roma International Symposium on EMC, September 1998, pp. 129-132.
8   "Characteristics of magnetic signals detected on the ground during the Soviet nuclear high-altitude explosions," memorandum provided by Soviet scientists, February 2003.
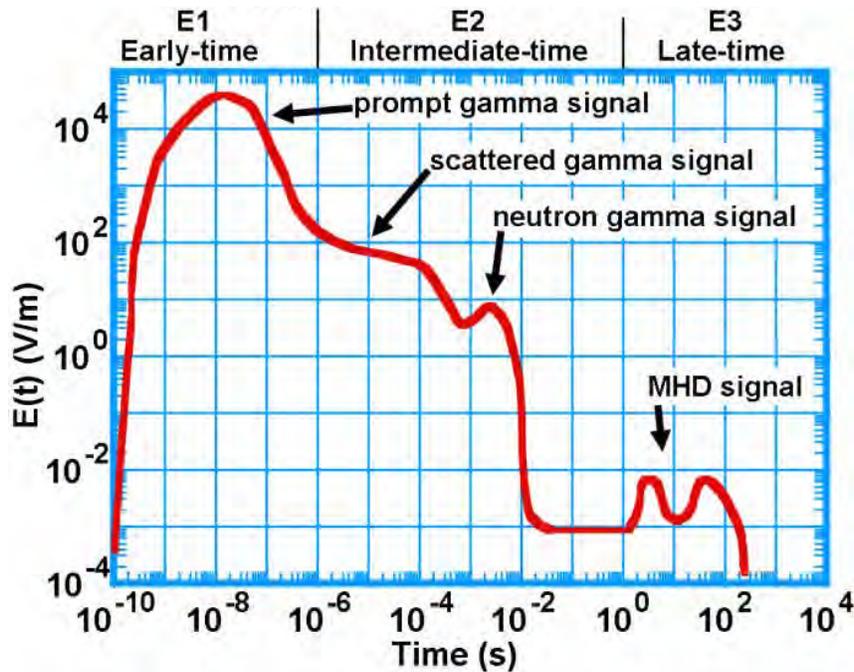
Figure 1 Parts of HEMP. E3 HEMP heave is roughly described by the second peak in the MHD signal. [SOURCE: Meta R-321]

In this report, the Soviet magnetic field data is reviewed, and through the use of several different ground conductivity profiles for locations in the U.S., the electric fields at the Earth's surface that could be induced are calculated. The magnetic fields are created by the nuclear detonation and the electric fields are induced in the earth and vary due to the particular deep conductivity profiles in the Earth. In addition, the magnetic fields (and electric fields) were also scaled to account for the fact that the Soviet measurements were not at the optimum ground locations to obtain the maximum peak fields on the ground. Finally, the increases in peak fields that would occur due to the well understood scaling of E3 HEMP with magnetic latitude were estimated, as the latitude of the Soviet tests were not at the bounding locations on the Earth.

The objective of this report is to determine from open source information how high the electric fields could be at latitudes of interest for the United States. In addition, a ground pattern and typical normalized electric field waveform is estimated that could be used for studies to determine the levels of quasi-DC currents that could be induced in long-line systems such as the bulk power system.
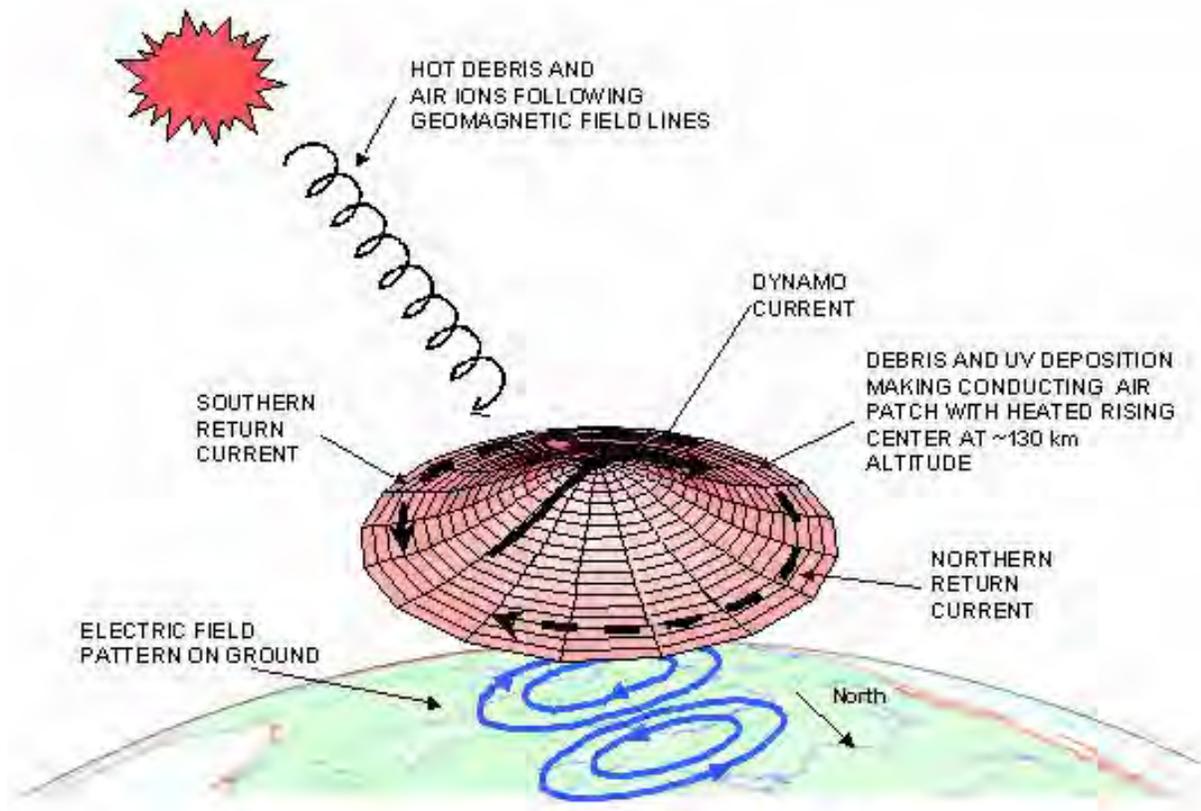
Figure 2 Diagram of the E3 HEMP heave effect. [SOURCE: Meta R-321]

This report does not claim that the values suggested here are absolute worst-case field levels, but rather these peak levels are estimated based directly on measurements made during high-altitude nuclear testing.

Figure 2 represents the E3 HEMP heave generation process. Hot ionized debris streaming downward away from the burst is directed preferentially along the geomagnetic field lines. As the debris and ultraviolet (UV) radiation from the burst reach altitudes where the atmosphere becomes dense enough, they heat up a "patch" of the atmosphere, and also add ionization to the background ionization already present in the ionosphere. The heat causes expansion, and the ionized region rises due to buoyancy. The Lorentz force on the ions and free electrons moving upward in the Earth's geomagnetic field leads to east-west dynamo currents, with return currents completing the current flow on the north and south side. These currents induce image currents, with the associated electric fields, in the conductivity of the Earth below. Associated with this are magnetic (B) fields. The levels of the generated E fields are dependent on the actual ground conductivity to great depths of the Earth below the heaving patch, while the associated B field perturbations are approximately independent of the ground profile. For
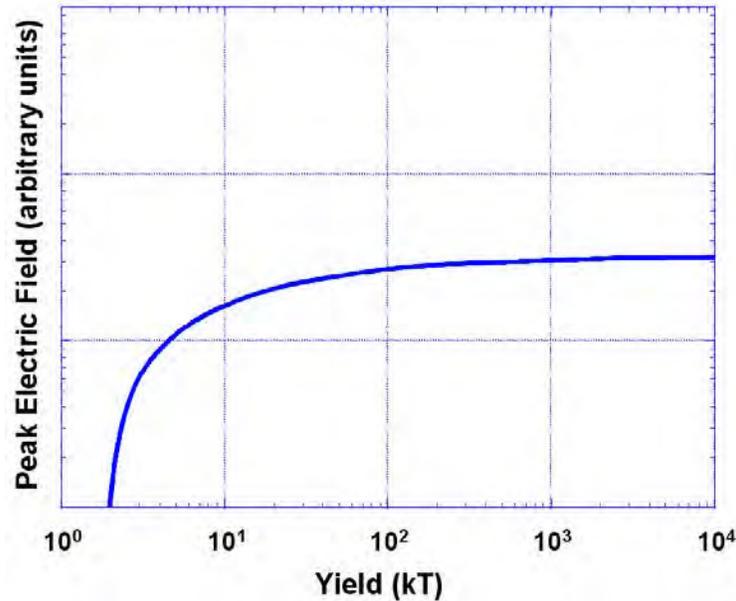
Figure 3 Sample normalized yield variation for maximum E field for heave for burst heights between 130 and 170 km and for a fixed Earth conductivity profile. [SOURCE: Meta R-321].

this reason, the measured B fields on the Earth's surface can be considered to be the principal E3 HEMP heave environment.

It is noted that there is a second mechanism that creates E3 HEMP fields on the ground called "Blast Wave", but while it also can produce significant B fields, the maximum fields are found thousands of kilometers away from ground zero. For this reason, the Blast Wave phenomenon is not considered in this report.

The E3 HEMP heave B field perturbation on the ground depends on many parameters, such as:

1. Burst parameters: The characteristics of the burst are important. Of primary importance is the burst yield—bigger bombs would tend to have more debris coming down and generating the E3 HEMP heave signal. Figure 3 shows a sample of E3 HEMP heave variation with yield. This yield dependence can vary with the burst height. In addition, the area of coverage for the peak field tends to be larger for larger yields.

2. Burst location: The burst location has two important effects. First, the height of burst (HOB) is important for E3 HEMP heave, as it is for other HEMP phenomena. The precise interaction with the atmosphere depends on how high the burst is above the atmosphere. Also, the higher the burst, the farther north (for northern hemisphere bursts) the heated patch is found, as it needs to travel a further distance on the tilted
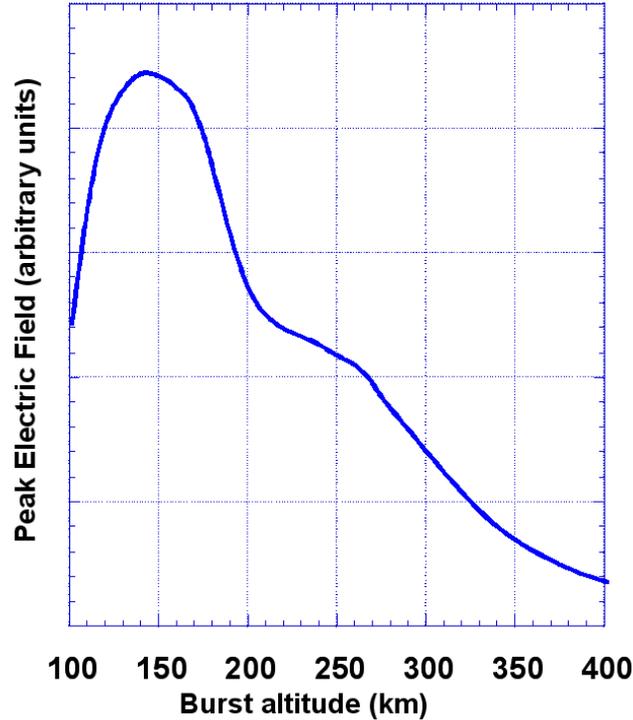
Figure 4 Sample normalized HOB variation for maximum peak E field for heave for an intermediate yield weapon and for a fixed Earth conductivity profile. [SOURCE: Meta R-321].

geomagnetic field lines. Figure 4 shows a sample of HOB variation for a fixed yield and ground conductivity profile. The other important location effect is the local geomagnetic field, which is represented by the value of geomagnetic latitude. One effect is that E3 HEMP heave gets weaker as the burst gets closer toward the (geomagnetic) poles, because the geomagnetic field becomes less horizontal, and there is less east-west deflection of the rising hot ions. (The geomagnetic latitude also affects the tilt of the path that the debris follows downward from the burst.)

3. Observer location: As seen in Figure 2, there is a 2-loop pattern of ground fields. The magnitude of the ground fields decreases with distance from the point directly below the patch. Examples of ground patterns are provided later in this report.

4. Burst time of day: Here the important factor is the "atmosphere", basically the state of the ionosphere, which can vary significantly. Depending on the burst time, the day of the year, and the location, the burst may be in "night" or "day". Sun exposure enhances the ionization of the ionosphere. For the E3 HEMP Blast Wave (the early-time portion of the E3 HEMP, which is not the subject of this report) the enhancement due to the "daytime" conditions depresses the E3 HEMP Blast Wave field, while for E3 HEMP heave there is an enhancement of the fields.

2   GROUND CONDUCTIVITY PROFILES

The E3 HEMP signal of concern in this report is the induced horizontal electric (E) field, as this field can effectively couple to long power and communications lines and induce quasi-dc currents in these systems. This coupling process has been discussed in several references including one that deals with geomagnetic disturbances (GMDs); GMD electric fields are similar in their time and frequency content to the electric fields produced by the E3 HEMP heave.[9] These E fields are produced by the presence of the conductivity depth profile in the Earth itself. For E3 HEMP heave it is the conductivity down to great depths (400-700 km) below the Earth's surface that determines the electric field. The E3 HEMP generation process begins with magnetic field (B) perturbations (relative to the geomagnetic field created by the Earth's core), and at the Earth's surface these B fields are little affected by the ground conductivity profile. Thus both calculations and measurements for actual nuclear tests typically begin with the B fields, and then E fields can be calculated for any assumed ground conductivity profile. While the induced peak E field is strongly related to the time derivative (dB/dt) of the horizontal B field, these calculations use the full Maxwell's Equations to determine the electric fields. The resulting E field is also horizontally oriented. The calculation of E from B must be done in terms of vector components—a B field in one horizontal direction creates an E field that is perpendicular to it under an assumed one-dimensional approximation for the local Earth conductivity profile.
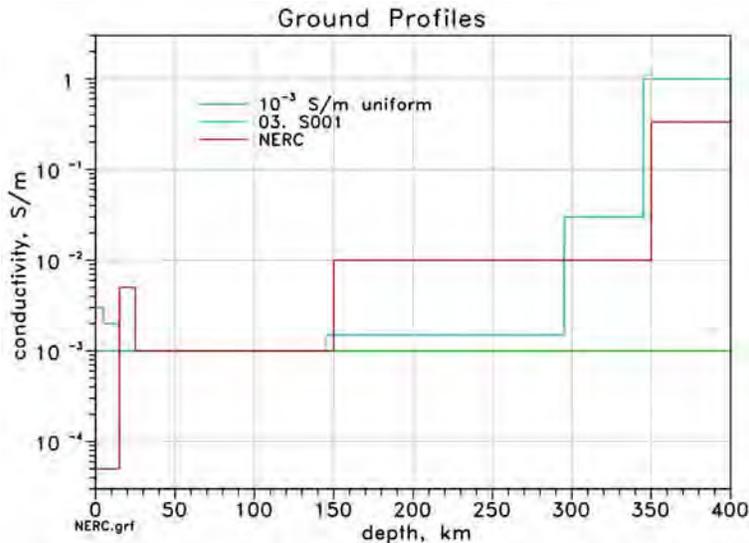
Figure 5 Ground conductivity depth profile for three ground profiles.

Figure 5 shows three ground profiles of ground conductivity with depth used in this report. The NERC profile (red line) has four layers of various conductivity levels, ending at a high

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[9]   W.A. Radasky, "Overview of the Impact of Intense Geomagnetic Storms on the U.S. High Voltage Power Grid," IEEE Electromagnetic Compatibility Symposium, Long Beach, California, 15-19 August 2011, pp. 300-305.
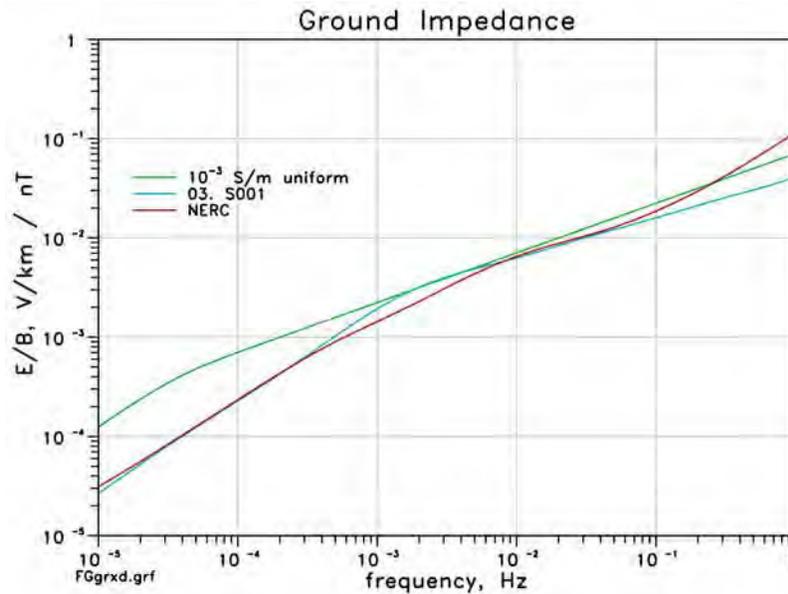
Figure 6 Ground profile B-to-E conversion in the frequency domain for three cases.

conductivity level that continues downward at its last value.[10] The E3 HEMP heave signals (due to their low frequency content) can penetrate through the upper layers of the Earth but will not penetrate much deeper when they encounter a high conductivity lower level (due to the pressures and temperatures found in the upper mantle of the Earth). The blue line is another set of ground conductivity data applicable to eastern Canada developed by Metatech from geological data. The impedance curve developed from this conductivity profile is seen to be very similar to the NERC curve in Figure 6. The third profile shown (in green) has a uniform conductivity of 10^{-3} S/m, which is used for simplicity in the E3 HEMP heave simulations shown later in this report.

Figure 6 shows the resulting impedance (conversion of B to E) in the frequency domain. There are many ways to deal with these types of impedance curves relating E to B, although the technique used by the authors allows calculations of E from B in the time domain without converting to the frequency domain.[11] This has advantages for performing real-time computations when measuring geomagnetic storm disturbances. All three curves are reasonably close together for the important frequency range of 1 to 100 mHz, as this is the frequency range of typical E3 HEMP B-field disturbances.

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[10]   "Transmission System Planned Performance for Geomagnetic Disturbance Events", TPL-007-1, available at https://bit.ly/2GQpQF1
[11]   J.L. Gilbert, W.A. Radasky and E.B. Savage, "A Technique for Calculating the Currents Induced by Geomagnetic Storms on Large High Voltage Power Grids," IEEE EMC Symposium, Pittsburgh, August 2012, pp. 323-328.

3   SOVIET E3 HEMP MEASUREMENTS

Toward the end of the development of the E3 HEMP computational models in the U.S., a paper that reported measurements made by the Soviet Union during two of their high-altitude nuclear tests in 1962 was provided to us through the U.S. Congressional EMP Commission by Soviet scientists.[12] This was high quality data, in that measurements were made at three fixed locations (designated N1, N2, and N3 by the Soviets as shown in Table 1 and Figure 7), and the B field measurements were provided for two horizontal vector components. There is some uncertainty concerning the precision of the test and measurement locations; however, the data provided greatly increased the information describing the E3 HEMP heave signal. High-altitude nuclear tests were performed by the U.S. mainly over the Pacific Ocean, and the locations for measuring the magnetic fields were not as diverse as for the Soviet measurements.

TEST PARAMETERS

The Soviet tests were reported to be at burst heights of 150 and 300 km altitudes, for the same device design with an estimated yield of 300 kT. The precise geometry (burst and observer locations) is not known, as there was some ambiguity in the data provided. The Soviet measurement paper does give range values (burst to observer distances) for all six measurements (three from each test), and these same values appear elsewhere in a consistent manner. (The Soviets tended to use the slant range from the burst to the ground location, not the ground range, but the ground range is easily calculated from the burst height.) A set of locations was used that are consistent with these values in the following discussions, using the understanding of the variation of the fields with location. These burst and observer locations are given in Table 1.

Table 1 Geometry for the Soviet High-Altitude Tests.

Test Locations			
Type	Position	Latitude (N)	Longitude (E)
Bursts	R1, 300 km	47.6°	64.9°
	R2, 150 km	47.0°	68.0°
Observers	N1	47.9°	67.4°
	N2	47.1°	70.6°
	N3	45.9°	72.1°

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[12]   "Characteristics of magnetic signals detected on the ground during the Soviet nuclear high-altitude explosions," memorandum provided by Soviet scientists, February 2003.

Using the simulation code in Meta R-321, the B field peak values were calculated for the two burst heights. The data is shown in Figure 7 for the 150 km burst height (R1) and in Figure 8 for 300 km (R2).[13] (The 300 km test was actually performed 6 days before the 150 km test, but the lower altitude case was described first). The peak contours are identified by their color, and the B field directions at the time of the peak are shown by the arrows. The burst and observer points are marked on the displays. Normalized results are shown in these figures as a nominal contour plot is desired to be used later in this report as a standard contour profile.
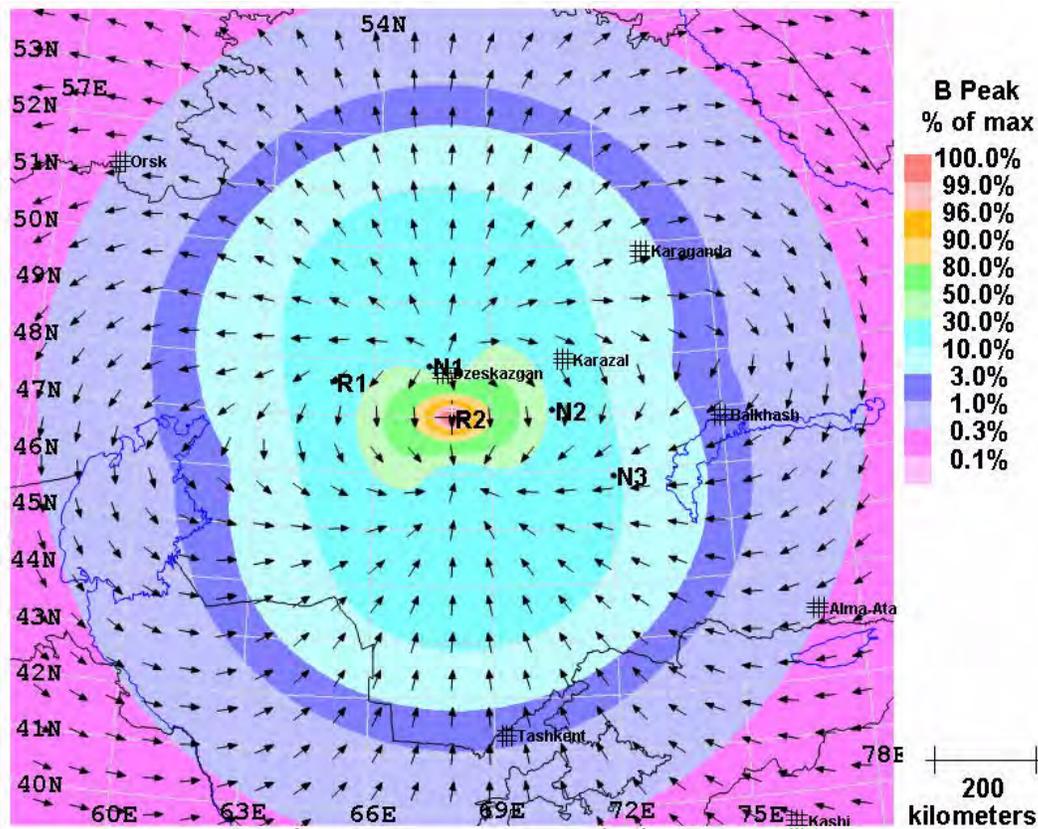
Figure 7 Simulation of the Soviet tests showing B field peaks and field directions,150 km test (R2).

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[13]   J.L. Gilbert, W.A. Radasky, K.S. Smith, K. Mallen, M.L. Sloan, J.R. Thompson, C.S. Kueny and E. Savage, "HEMPTAPS/HEMP-PC Audit Report." Meta R-131, December 1999; DTRA-TR-00-1, April 2002.
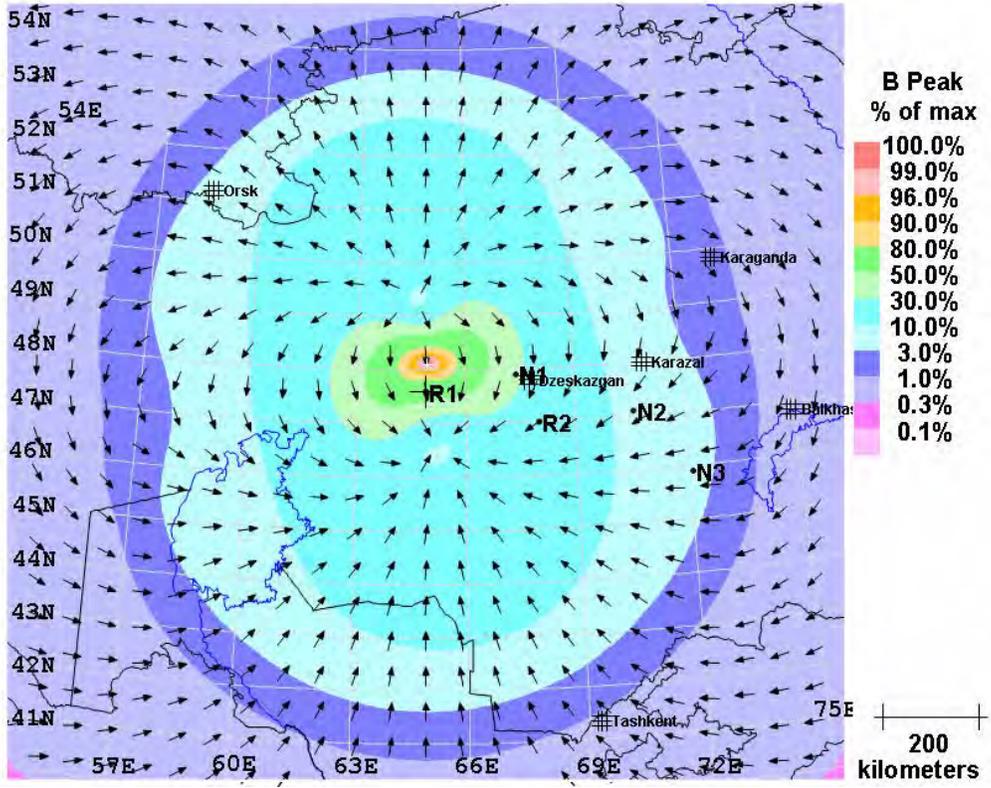
Figure 8 Simulation of the Soviet tests showing B field peaks and field directions, 300 km test (R1).

The next set of figures shows the measured B field time waveforms. The three lines are the north and west components, and the resulting magnitude. For the 150 km burst height case, shown in Figure 9 to Figure 11, the waveforms are all relatively wide in pulse width (the N1 case waveform has not returned to zero at the end of the 100-second window of the measurements). The peak occurs between times of 35 to 70 seconds. Figure 7 shows that N1 is close to the northern area of the two electric field depression points (the locations around which the two loops of E field circulate, as seen earlier in Figure 2) for this case. Here the time waveform may be complicated due to some shifting with time of the field depression point position. For the 300 km burst height waveforms, Figure 12 to Figure 14, the signals are faster, especially for N1. As noted, faster rising waveforms for the B fields enhance the E fields, because the impedance of the Earth behaves as $f^{1/2}$ (f = frequency) as shown in Figure 6.
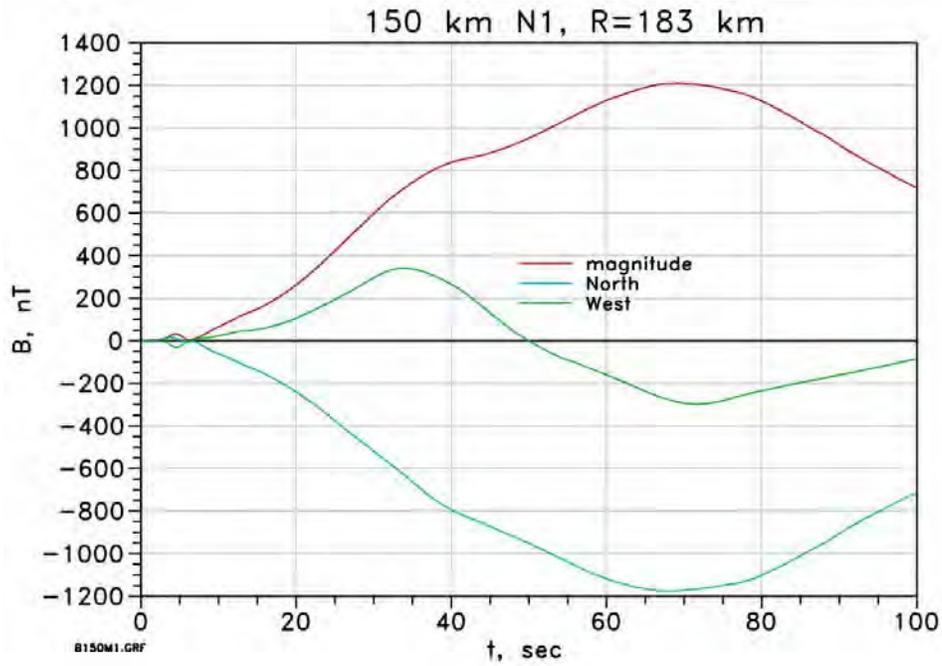
Figure 9 Measured B fields at N1, 150 km test.
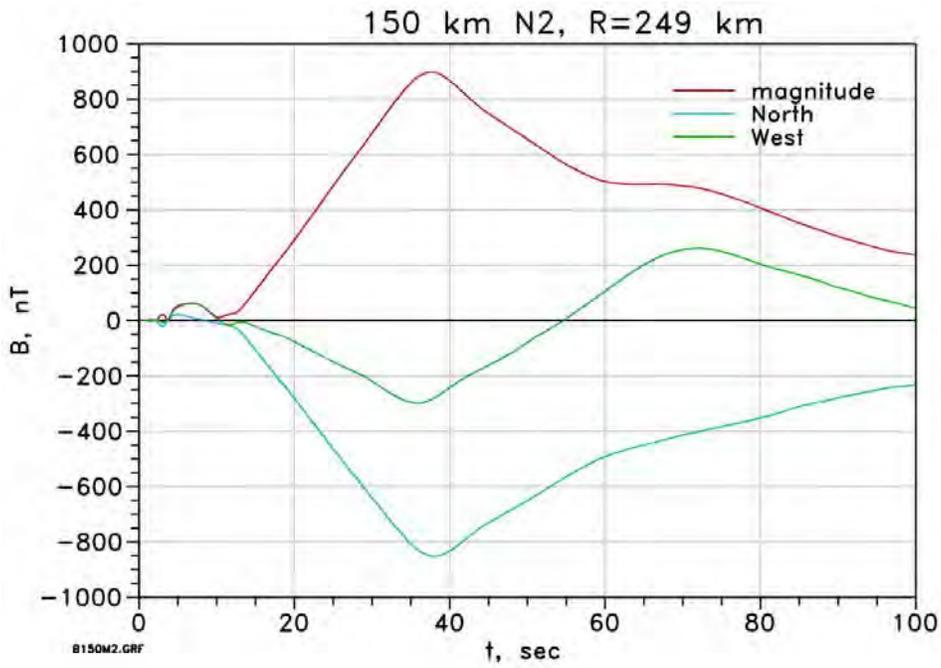
Figure 10 Measured B fields at N2, 150 km test.
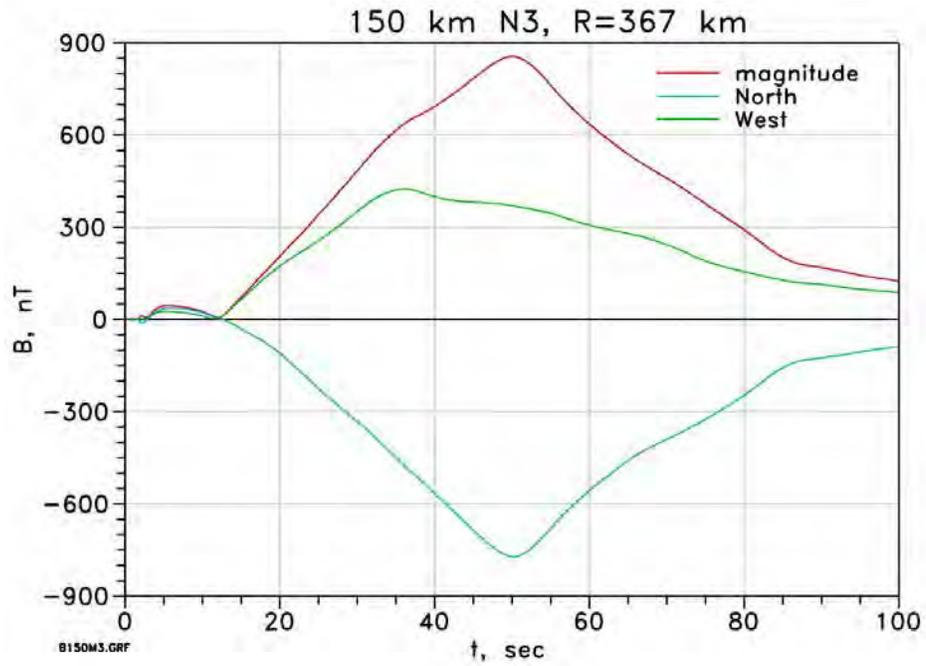
Figure 11 Measured B fields at N3, 150 km test.
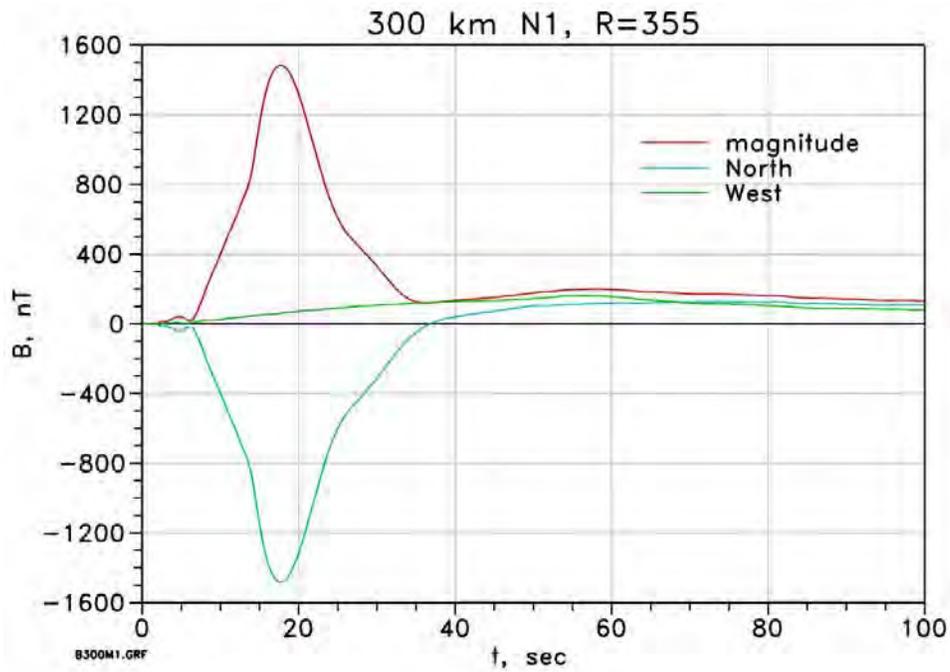
Figure 12 Measured B fields at N1, 300 km test.
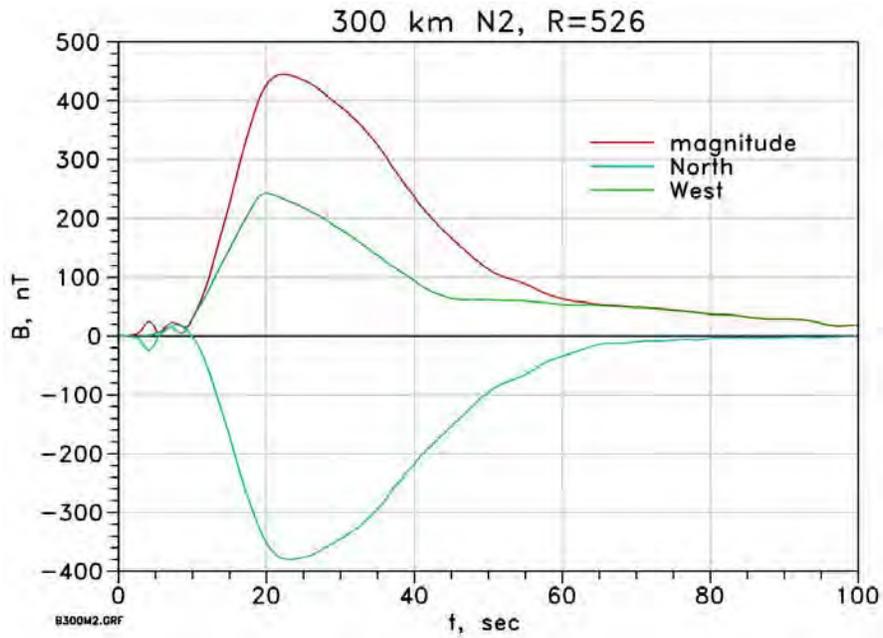
Figure 13 Measured B fields at N2, 300 km test.
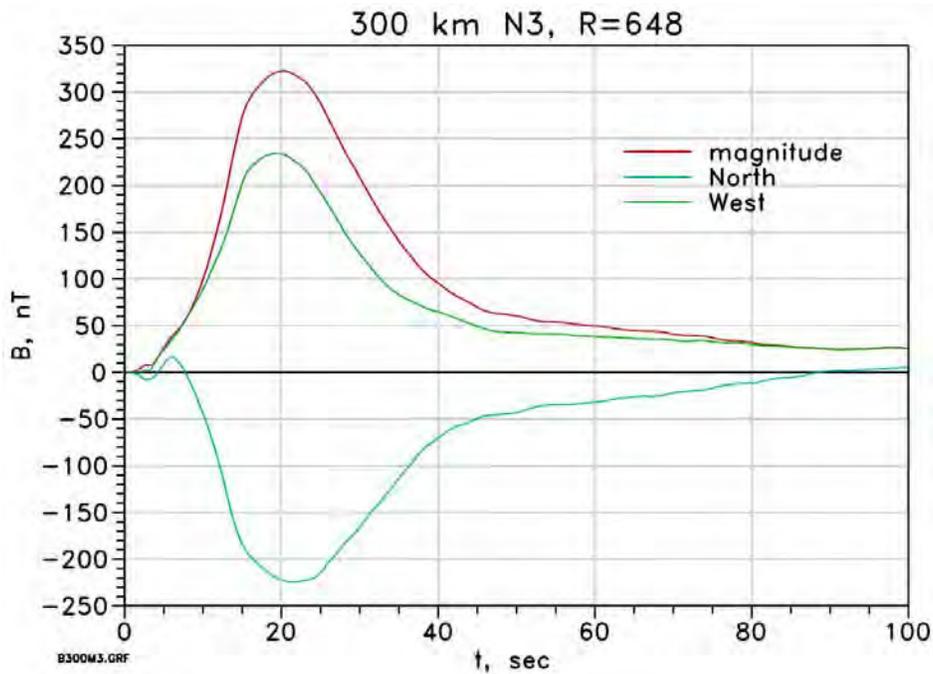
Figure 14 Measured B fields at N3, 300 km test.

The electric fields are now calculated from the measured B fields, given in nanoTeslas (nT). Table 2 lists the peak values for the calculated E fields, along with the peak values for the measured B and B-dot. The time derivative of B is often a good proxy for the behavior of the peak value of the electric field for a given ground conductivity profile. That is to say that for a given profile increases in the time derivative of the B field result in higher peak electric fields. It is noted, however, that the rest of the computed time waveform of the electric field depends more on the shape of the impedance curve and using the time derivative of the B field to compute the entire electric field waveform will not result in an accurate E field waveform.

For the following plots the measured B field components were individually computed for four sample ground profiles (a fourth severe ground profile and impedance curve was added to the previous set of three), and the resulting E field magnitudes are plotted (the total horizontal electric field is calculated by separately calculating the electric fields from the two orthogonal B field components). The 150 km cases are presented in Figure 15 to Figure 17, and the 300 km cases are presented in Figure 18 to Figure 20. These show that E fields are similar for the three ground profiles described in Figure 6. Further, the dark blue line shows the E field for a ground profile that has a very low conductivity. This profile was developed for southern Sweden and has also been used for a limited region in the northeastern United States, but it has not been used to develop the E3 HEMP results here. It is presented only to indicate that large electric fields are possible in some locations.

The highest computed E fields are for the N1 observer for the 300 km burst case. This had the highest measured B fields, and also had the narrowest time waveform—the computed peak E fields are driven higher by the enhanced time derivative of the B.

Table 2 Peaks of the Soviet measurement waveforms. (The E field is for the 10^{-3} S/m ground.)

Measurement Peaks

Burst	Observer	Peaks		
		B, nT	$\dot{B}$, nT/min	E, V/km
R2 150 km	N1	1208.99	2141.2	4.885
	N2	898.27	3526.3	5.580
	N3	856.08	2240.2	4.241
R1 300 km	N1	1484.05	17581.4	16.585
	N2	444.69	3064.8	4.110
	N3	322.57	2642.9	3.113
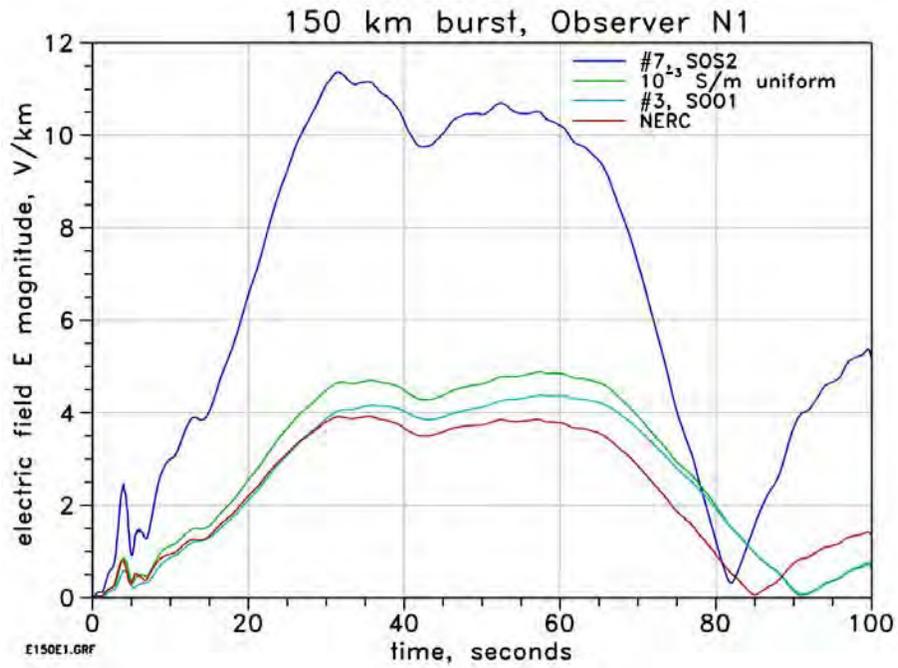
Figure 15 E field amplitudes for four ground profiles, at N1, 150 km test.
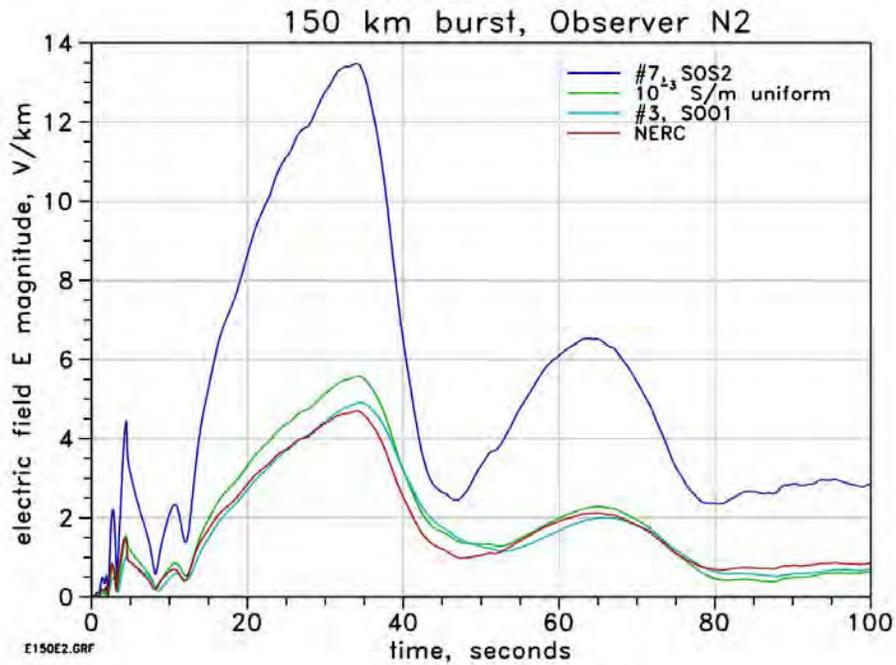
Figure 16 E field amplitudes for four ground profiles, at N2, 150 km test.
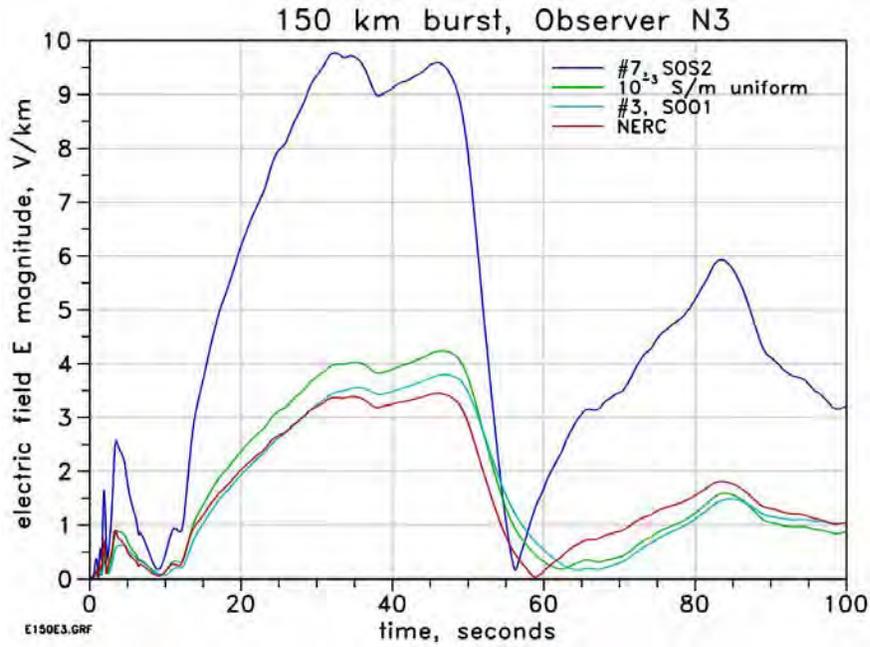
Figure 17 E field amplitudes for four ground profiles, at N3, 150 km test.
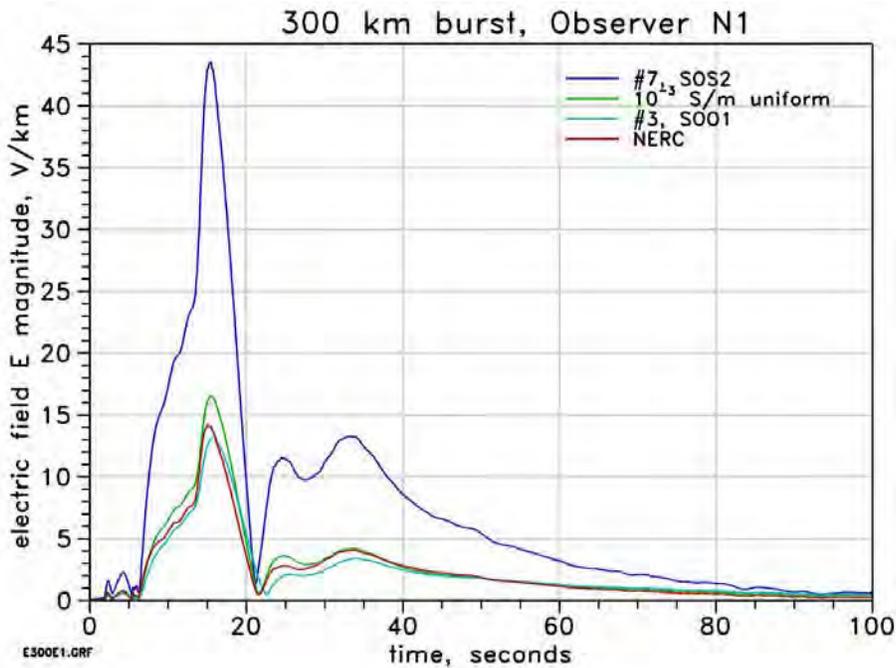
Figure 18 E field amplitudes for four ground profiles, at N1, 300 km test.
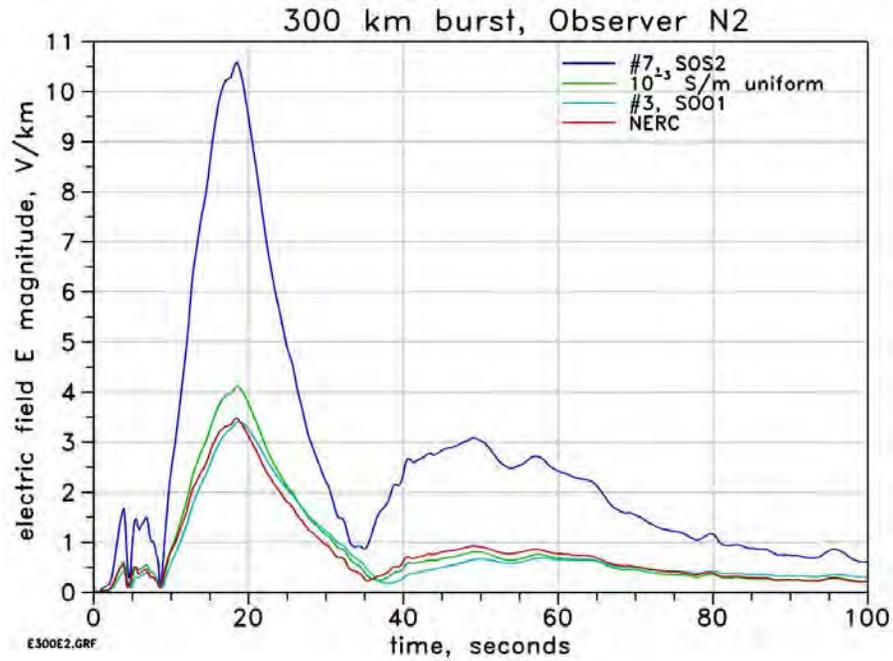
Figure 19 E field amplitudes for four ground profiles, at N2, 300 km test.
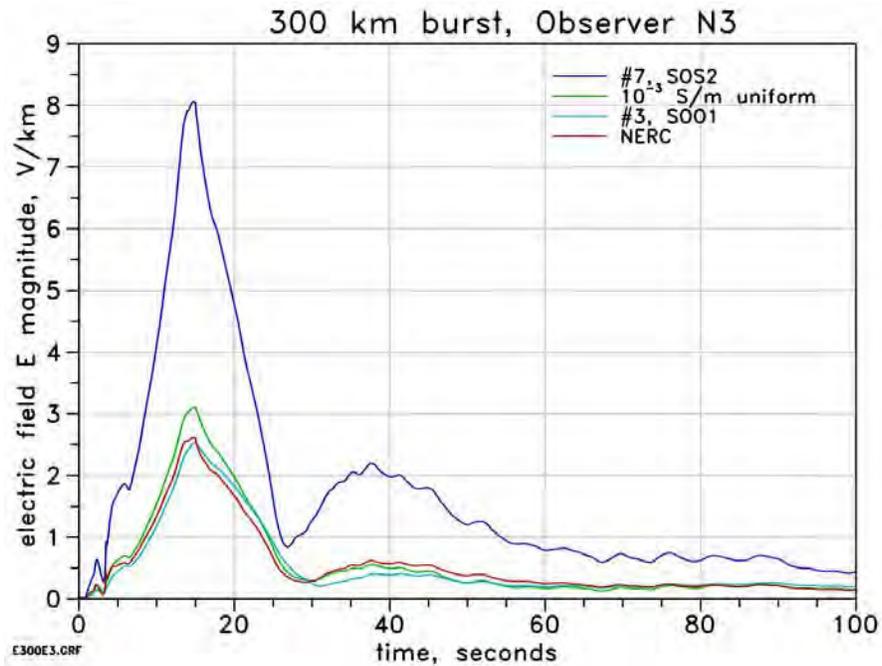
Figure 20 E field amplitudes for four ground profiles, at N3, 300 km test.

SCALING OF THE RESULTS

Even at this date the calculational models of E3 HEMP heave are not considered to be perfect, and therefore measurements are the most believable evidence of possible E3 HEMP heave field levels. However, it is extremely unlikely that even these few high-quality measurements captured the highest peak fields. Of course other test devices, especially with higher yields, could have produced higher fields, and there can be vast variations in the atmosphere conditions. For this report, the parameters of interest are the locations of the measurement observers and of the burst itself. Specific parameters are the impacts due to the geomagnetic latitude of the bursts, and whether a better location exists to place measurement sites relative to each burst. The first question is: how much higher could the measured fields have been if the burst location were closer to the geomagnetic equator? The second question is because the fields were measured at only three locations, none of which were likely to have been at the optimum point, can the measurements be scaled to the optimum point?

LATITUDE SCALING

The first consideration is the geomagnetic latitude. The geomagnetic latitude values for the two cases are found from the given physical locations:

150 km: 48.92° N
300 km: 46.13° N

These values depend on knowing the burst locations, for which there is some uncertainty, but the precise values were likely within a few degrees of these values. As discussed, the maximum peak magnetic fields increase for lower geomagnetic latitudes per the basic models.

Considering the 150 km burst case, Figure 21 shows the equivalent locations for the continental U.S. The marked red lines show geomagnetic latitude lines, and there is a black line for the 48.92°N magnetic latitude corresponding to the 150 km HOB Soviet test. If the burst had been placed anywhere along this line, the maximum peak B fields would have been as in the Soviet test. For bursts below (south) this black line, the fields would be higher.

The map shows that Texas and Florida can be as low as 35°N geomagnetic latitude. The simulation code used to perform the calculations was the same as used for the simulations shown in Figure 7 and Figure 8, but with the burst moved to lower geomagnetic latitudes— specifically the cases of 35°N that correspond to the southern points for Florida and Texas, and also for the highest levels worldwide (the geomagnetic equator). Next, the ratios of the maximum B fields from these simulations at other latitudes were compared to the maximum values for the Soviet measurement location, to get the results shown in Table 3. Using these ratio values, the Soviet measurements ("Soviet" column) were scaled to the corresponding maxima for the other latitude burst locations.
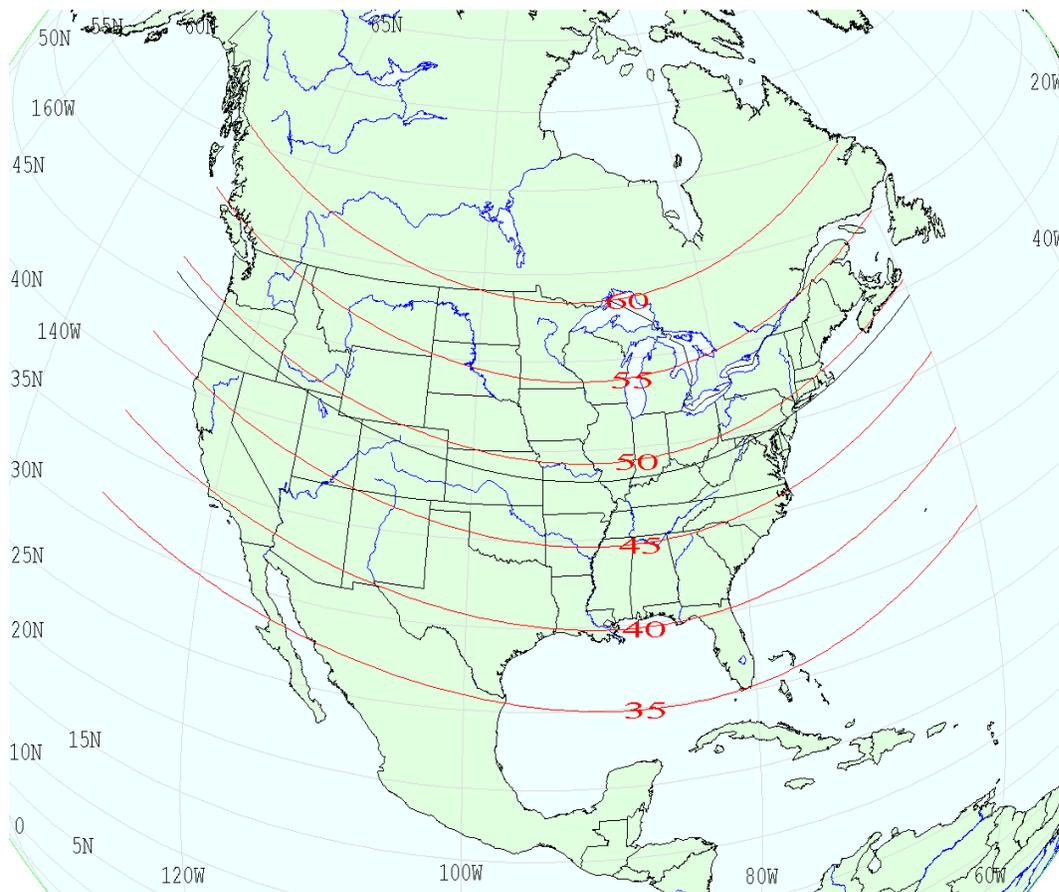
Figure 21 Geomagnetic latitude variation, for a 150 km burst, over the U.S. The black line is at 48.92°, which is the computed geomagnetic latitude for the 150 km Soviet test.

Locations outside of the continental U.S. include both lower and higher geomagnetic latitudes. The table therefore includes scaling for a magnetic latitude of 22° N, which is appropriate for Oahu, Hawaii, and also for a magnetic latitude of 65° N, as would apply to Fort Greely, Alaska.

PATTERN SCALING

The burst locations were different for the two tests, but the three observer locations stayed the same for the two tests. There is some uncertainty, however, in both the burst points and observer points. However, it is likely that the fields were higher at locations other than the three places that happened to be selected for the measurement sites. Here some understanding is sought for how high the measured fields might have been if there was a measurement at the optimal location. Figure 7 (the 150 km case), for example, shows that for this HOB the maximum is close to being directly under the burst, but the measurement sites were further out.

Table 3 Geomagnetic latitude scaling of the Soviet measurements.

Scaling of Measurements to Other Magnetic Latitudes

Burst (km)	Observer	Soviet, B, nT	Alaska, 65° N		U.S., 35° N		Hawaii, 22° N	
			Scaling factor	B, nT	Scaling factor	B, nT	Scaling factor	B, nT
R2 150	N1	1208.99		725.28		1648.65		2025.50
	N2	898.27	0.600	538.88	1.364	1224.93	1.675	1504.93
	N3	856.08		513.56		1167.40		1434.24
R1 300	N1	1484.05		855.62		1890.47		2280.36
	N2	444.69	0.577	256.38	1.274	566.47	1.537	683.29
	N3	322.57		185.98		410.91		495.66

As noted, there is some uncertainty in the modeling and for the model parameters to use to simulate the Soviet tests. Good confidence exists, however, in the values for the ranges to the measurement sites. With this in mind, the simulation shown in Figure 22 performs E3 HEMP heave calculations at points on a 2D polar mesh; for each range of this mesh all the azimuth angles were searched to obtain three norm values: maximum, average, and minimum. The overall maximum was identified and the three norm values were normalized to this maximum value, to obtain the three lines in the plot.
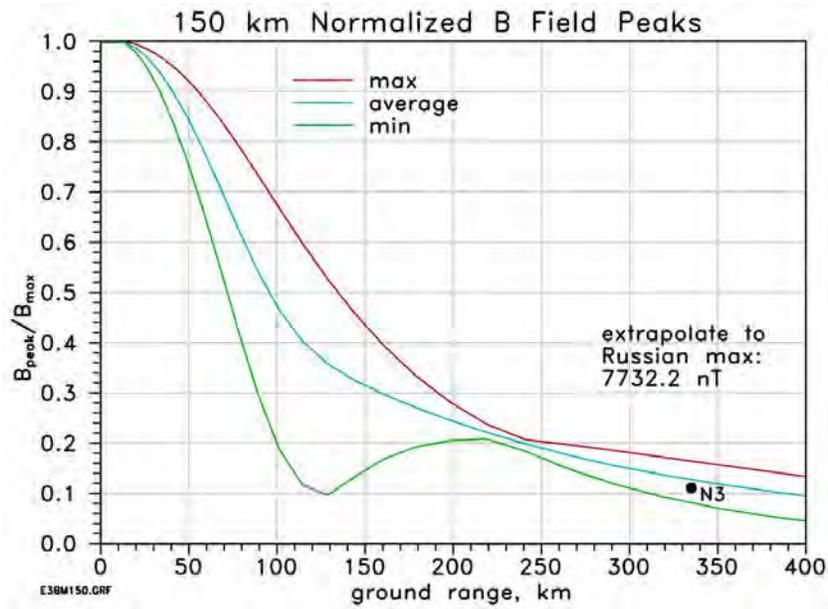
Figure 22 Normalized simulated B field peaks versus ground range for the 150 km test. The black dot
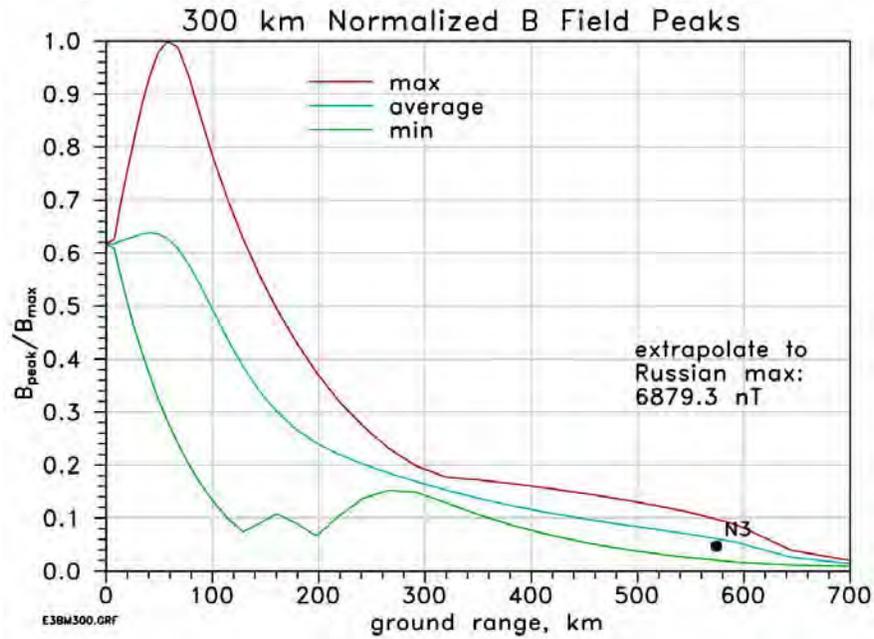
Figure 23 Normalized simulated B field peaks versus ground range for the 300 km test. The black dot shows the simulated results for the N3 point.

As noted, the precise observer azimuth positions are unknown, but the normalized value for the assumed position of the N3 observer is shown (the black dot) using a best-estimate location. Note that at this range there is not as much structure to the azimuth variation as there is closer in, such as at the 120 km range, so there is less uncertainty associated with the exact azimuth position for N3. Another way of stating this is to observe that the contour pattern becomes more circular as the observer is further away from surface zero. Using this pattern, the estimate for the maximum is then given by scaling with the factor of 9.03 (1/0.111) from the N3 point to the optimum position. The same method was used for the 300 km burst height, in the plot shown in Figure 23.

Table 4 summarizes the scaling for the two cases. The scaled values are listed in the last column. These are found by multiplying the N3 measurements (the 3rd column) by the scaling

Table 4 Pattern (observer position) scaling of the Soviet measurements.

Scaling from N3 up to the Maximum Point				
	Soviet Measurements		Scaling	
Case	N1, B (nT)	N3, B (nT)	Scaling Factor	Max, B (nT)
R2, 150 km	1209.0	856.08	9.03	7732.2
R1, 300 km	1484.0	322.57	21.33	6879.3

factors (4th column, given by the reciprocal of the N3 values in Figure 22 and Figure 23). For comparison, the maximum measured values are listed in the 2nd column (the N1 points). The fact that these are smaller than the scaled maximum values is an indication that none of the observer points were very close to the optimum position.

4   CONCLUSIONS

The Soviet measurements of the E3 HEMP heave B fields were converted to E fields for a reasonable bounding case of a uniform ground conductivity of 1 mS/m. None of the three measurement points of the E3 HEMP heave fields were near the maximum in the expected field pattern, and column 3 in Table 5 gives estimates of the scaling of the measurements to the expected maximum. The three right columns provide the scaling for magnetic latitude to Hawaii, the southern portion of the continental United States, and Alaska.

Table 5 Scaling of the Soviet Measurements.

Scaling from N3 up to the Maximum Point, for Three Latitudes for 10^{-3} S/m					
	Soviet Measurements		Latitude Scaling, E, V/km		
Case	Latitude (N)	E, V/km	22° N	35° N	65° N
R2, 150 km	48.92°	38.31	64.18	52.24	22.98
R1, 300 km	49.10°	66.39	102.02	84.57	38.28

Figure 24 provides a normalized waveform for one of the E fields. The electric field waveform can be used when computing the induced currents flowing in power lines, for example, to determine the amount of heating in transformer hot spots, as the time dependence of the currents are important in determining thermal effects. Figure 25 provides a sample normalized ground pattern, showing the spatial fall-off from the maximum value. Note that
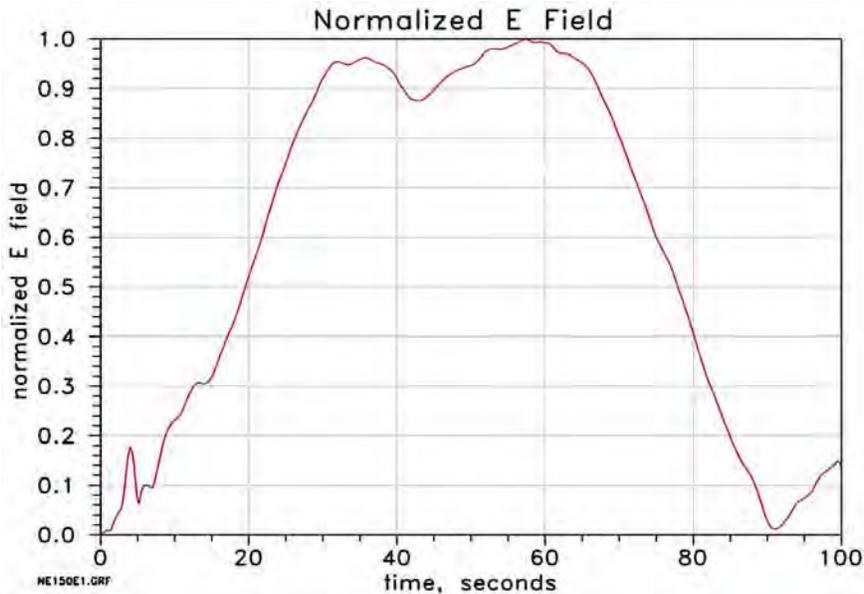
Figure 24 E field waveform shape, using the measured N1 waveform from the 150 km burst height
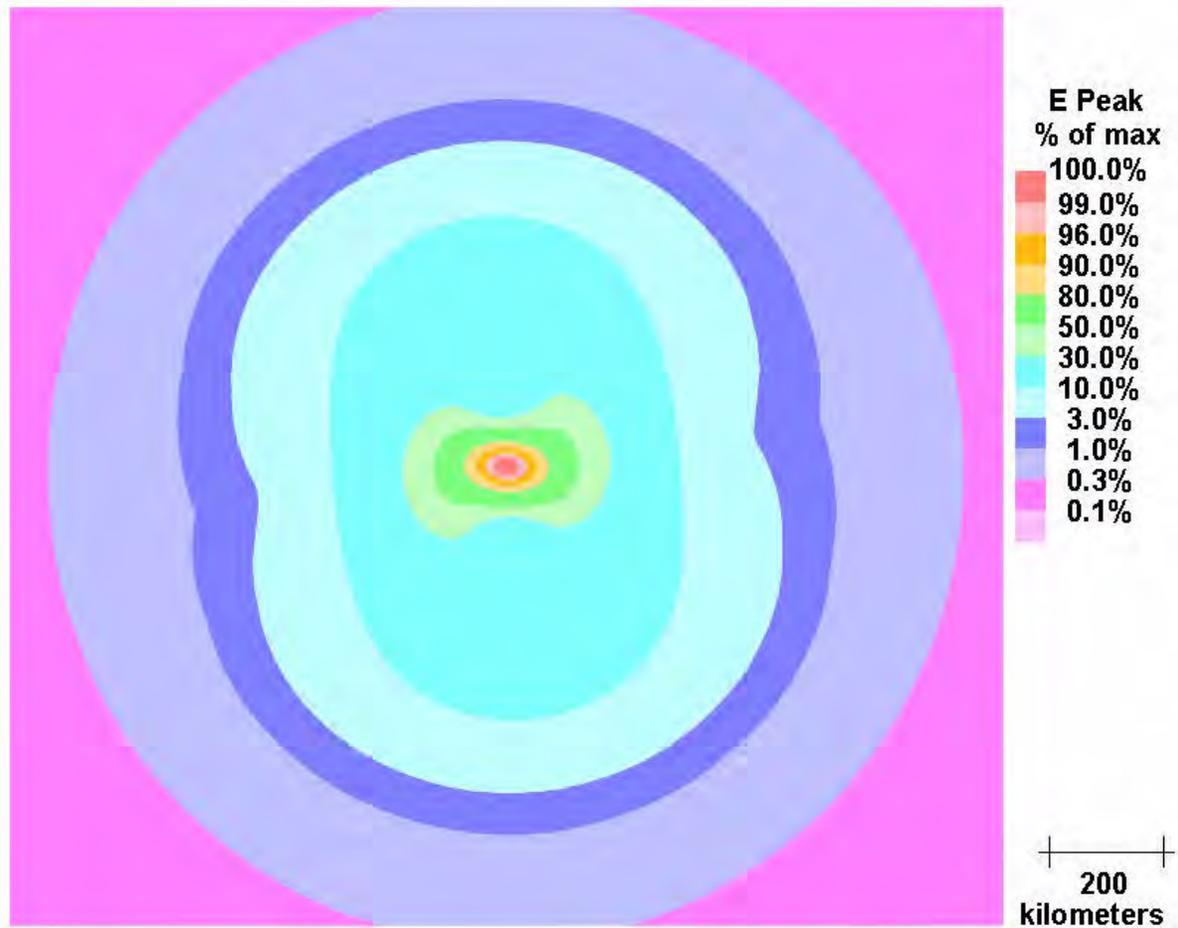
Figure 25 Normalized E peak contour pattern from the 150 km burst case

higher yield bursts could lead to even higher maximum fields, although as shown in the generic curve in Figure 3, the peak value tends to saturate as yields increase. However, this is not true for area coverage, as increasing to larger yields can increase the spatial extent of the high field region.

Exhibit E

Abstract from "Standard late-time HEMP waveform, International Electrotechnical Commission IEC 61000-2-9, Edition 2.0, 2025-05
(Entire standard incorporated by reference).

Abstract

IEC 61000-2-9: 2025 defines the high-altitude electromagnetic pulse (HEMP) environment that is one of the consequences of a high-altitude nuclear explosion. There are two cases of nuclear detonations:
- high-altitude nuclear explosions;
- low-altitude nuclear explosions.

For civil systems, the most important case is the high-altitude nuclear explosion. In this case, the other effects of the nuclear explosion such as blast, ground shock, thermal and nuclear ionizing radiation are not present at the ground level. However, the electromagnetic pulse associated with the explosion can cause disruption of, and damage to, communications, electronic systems, electric power systems and other portions of the commercial critical infrastructures, thereby upsetting the stability of modern society. The object of this document is to establish a common reference for the HEMP environment in order to select realistic stresses to apply to victim equipment for evaluating their performance and in order to develop protection methods to minimize the impacts of the HEMP. This second edition cancels and replaces the first edition published in 1996. This edition constitutes a technical revision. This edition includes the following significant technical changes with respect to the previous edition:

a) updating the document to provide new information on the variation of the early-time HEMP on the earth's surface and to provide new information on the late-time HEMP;

b) adding a new informative Annex A which provides details concerning the development of the early- and late-time standard waveforms in the main body, an explanation of the advantages and disadvantages for the use of the double exponential waveform, and an explanation of the far field region for the early-time HEMP.

IEC 61000-2-9: 2025 has the status of a basic EMC publication in accordance with IEC Guide 107.

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Exhibit F

U.S. Senate Committee on Homeland Security and Government Affairs, Statement by Dr. Justin Kasper. February 27, 2019.

U.S. Senate Committee on Homeland Security and Government Affairs
Roundtable: Perspectives on Protecting the Electric Grid from an Electromagnetic Pulse or
Geomagnetic Disturbance
Statement by Dr. Justin Kasper (University of Michigan)

Introduction

Chairman Johnson, Ranking Member Peters, and members of the Committee, thank you for this opportunity to discuss what we know about the solar origin of geomagnetic disturbances (GMD) and how we can improve our ability to predict their occurrence.

The most famous example of a solar GMD began on September 1, 1859, when an intense solar flare produced a visible white flash directly observed by the astronomer Carrington. Just 18 hours later material from the solar atmosphere released after the flare slammed into Earth at about three million miles an hour. Earth was engulfed in a magnetic tsunami from the Sun that sent compasses spinning, brought the Northern lights down into the Caribbean, and set telegraph lines sparking, rendering them inoperable for days. We might not rely on telegraph today but our power lines are equally susceptible. The potential nation-wide and even world-wide loss of power due to a Carrington-level event and the resulting economic and societal impact are why we are here today.

The risk is real and unfortunately the Carrington event was not unique. On July 23, 2012 a spacecraft operating on the other side of the Sun was immersed in a similar eruption that would have hit Earth square on if it had happened nine days sooner. Multiple researchers estimate the probability of a similar event happening in any decade at between 3 and 10 percent. I would like to stress that in addition to these extreme events, smaller but more frequent GMDs are estimated to cause an average of $10 billion in damage each year. Address the major GMDs and we can also protect us from these smaller events.

What can we do about this? Right now telescopes detect an eruption at the Sun and we make a forecast by simulating its expansion into space, but we do not have confirmation of a threat to Earth until it reaches the NOAA DSCOVR spacecraft floating one percent of the way towards the Sun. Any warning is better than none, but an extreme event would get from the spacecraft to Earth in less than ten minutes. This is not enough time to assess the risk and recommend action. We need spacecraft closer to the Sun providing earlier warning of Earth directed events and their properties, better models of these eruptions and regional forecasts of GMD. Most importantly we need leadership with a mandate to coordinate and direct the research and operational components of space weather that are spread over multiple agencies.

Overview

My written testimony is organized to address the following three questions.

1. How do public and private sectors evaluate the likelihood and magnitude of these events?
2. Is there ongoing research to help us better understand the solar phenomena that lead to space weather impacts on Earth?
3. How can current National Oceanic and Atmospheric Administration (NOAA) and/or National Aeronautics and Space Administration (NASA) programs improve GMD forecasting, mitigation, coordination, and response efforts?

1. How do public and private sectors evaluate the likelihood and magnitude of these events?

Evaluating the likelihood and magnitude of the most severe GMDs is challenging because the detailed record of direct observations only extends back half a century to the start of the space age, and because we are still in the early phases of understanding what aspects of a solar eruption and the Earth determine the severity of the resulting GMD. We are also still learning about the impacts of GMDs. For example an extreme space weather event in August 1972 known for its speed and intense particle radiation, did not generate a particularly large global GMD, but did produce a magnetic disturbance in Asia so strong that it spontaneously detonated dozens of sea mines south of Hai Phong, North Vietnam on 4 August 1972.[1] Within the research community the most accepted estimates of the probability of an extreme GMD are based on an analysis of the occurrence rate of historical GMDs as a function of severity, fit to a statistical model, and then evaluated at the extreme.[2] Quoting the Riley et al. (2018) study,

> Based on these results, our best estimate for the probability of another extreme geomagnetic event comparable to the Carrington event occurring within the next 10 years is 10.3% with 95% confidence intervals (CI) in the range [0.9,18.7] for a power-law distribution, but only 3.0% with 95% CI [0.6,9.0] for a log-normal distribution (see also Riley and Love 2017). Our results, however, depend on: (1) how an extreme event is defined; (2) the statistical model used to describe how the events are distributed in intensity; (3) the techniques used to infer the model parameters; and (4) the data and duration used for the analysis.

Thus depending on assumptions about the distribution of events the probability of an extreme Carrington level event within the next ten years ranges from 3% to 10%.

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[1] Knipp, D. J., Fraser, B. J., Shea, M. A., and Smart, D. F. (2018). On the little-known consequences of the 4 August 1972ultra-fast coronal mass ejecta: Facts, commentary, and call to action.SpaceWeather,16, 1635–1643.

[2] Riley, P., Baker, D., Liu, Y.D. et al. Space Sci Rev (2018) 214: 21. https://doi-org.proxy.lib.umich.edu/10.1007/s11214-017-0456-3. P. Riley, J.J. Love, Extreme geomagnetic storms: probabilistic forecasts and their uncertainties. Space Weather 15(1), 53–64 (2017)

In order to test these estimates other researchers are trying to increase the number of large events in the record by either looking at ancient records of activity earlier in Earth's history, or by simultaneously monitoring many other starts like our own Sun for large flares.

Large solar flares and coronal mass ejections can produce elevated levels of high energy particle radiation in space, factors of millions or more above typical levels. This level of particle radiation can cause measurable changes in the isotopic and chemical composition of the atmosphere which then are preserved through snowfall in undisturbed ice or ancient tree rings for millennia. Ice core samples in Greenland and Antarctica have been used to search for extreme events in the more distant past, although signals from other events such as major volcanic eruptions have made them hard to interpret. An isotopic analysis of tree rings has found elevated spikes in the level of the isotope Carbon-14 in the years 774 AD and 993 AD which may have been due to extreme solar events.[3]

In addition to calculating the probability of an extreme GMD, there have also been efforts to estimate the cumulative impact of smaller but more frequency GMDs. For example, Zurich Risk Engineering recently published an examination of over 11,000 insurance claims submitted by North American commercial organizations from 2000 through 2010 for equipment losses and related business interruptions associated with damage to, or malfunction of, electrical and electronic equipment.[4] The claims were then correlated with the level of geomagnetic activity. There is a very clear association, with claims up 20% for the top 5% most geomagnetically active days. This amounted to about $2B in claims over a decade seen by this one insurance company due to GMD induced electrical damage. Given that this insurance company only covers 8% of the market this suggests that GMD could be responsible for $2B a year in commercial property damage in the US.

2. Is there ongoing research to help us better understand the solar phenomena that lead to space weather impacts on Earth?

For reasons we do not yet fully understand the corona or extended atmosphere of our Sun is nearly 1000 times hotter than its surface. This million degree atmosphere is unstable and produces supersonic jets of plasma called the solar wind that expand into space and flood the solar system with particles and magnetic fields. Occasionally a highly magnetized region in the corona will erupt into space. These eruptions as called coronal mass ejections (CMEs) and they can produce the high speeds and magnetic fields that cause the most extreme GMDs. Variation in the solar wind over time and as the Sun rotates every 27 days can cause the Earth to be

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[3] F. Miyake, K. Nagaya, K. Masuda, T. Nakamura, A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan. Nature 486(7402), 240–242 (2012). F. Miyake, K. Masuda, T. Nakamura, Another rapid event in the carbon-14 content of tree rings. Nat. Commun. 4, 1748 (2013). F. Miyake, K.Masuda,M. Hakozaki, T. Nakamura, F. Tokanai, K. Kato, K. Kimura, T. Mitsutani, Verification of the cosmic-ray event in AD 993–994 by using a Japanese Hinoki tree. Radiocarbon 56(3), 1189–1194 (2014)

[4] Dobbins, R. and K. Schriiver, Electrical claims and space weather. Measuring the visible effects of an invisible force, June 2015

bathed in changing speed solar wind, which can also trigger smaller GMDs. The Earth is surrounded by the ionosphere, a region of space that contains charged particles and electric and magnetic fields. The ionosphere is surrounded by a region of space controlled by the magnetic field of the Earth, the magnetosphere. The magnetosphere and ionosphere are continually bathed in large fluxes of radiation, energetic particles and mass from the Sun. The conditions and changes in both these regions of space are referred to as space weather. As with terrestrial weather, space weather can often result in severe dynamic events, storms in space, many of which result in severe operational consequences for satellites and our technological infrastructure on the ground. Some of these events have the potential for catastrophic damage. A recent review of all research into the Sun and space weather can be found in the comprehensive 2013 National Academy of Sciences Decadal Strategy for Solar and Space Physics.[5] For a review of the state of the art in space weather research a recent special collection in Space Science Reviews titled "The Scientific Foundation of Space Weather" has a comprehensive review.[6]

New research capabilities that are posed to transform our understanding of the connection between the Sun and the Earth include the recently launched Parker Solar Probe mission in 2018.[7]   This spacecraft will repeatedly plunge into the extended atmosphere of the Sun, collecting the first direct observations of how the corona is heated and the solar wind accelerated, and directly observing coronal mass ejections as they erupt into space.[8] Parker Solar Probe will be joined next year by the Solar Orbiter mission, which will not get as close to the Sun but will image the surface at high resolution. Closer to Earth, the recently launched GOLD mission and the upcoming ICON mission monitor the response of Earth's upper atmosphere to changes in solar input. The community eagerly awaits the completion of the Daniel K. Inouye Solar Telescope (DKIST) solar telescope in 2020 and its unprecedented ability to image activity on the surface of the Sun and in its corona.

3. How can current National Oceanic and Atmospheric Administration (NOAA) and/or National Aeronautics and Space Administration (NASA) programs improve GMD forecasting, mitigation, coordination, and response efforts?

As is often the case, the distribution of work across multiple agencies can hinder progress. In the case of space weather research a major challenge is that it is difficult for NOAA to fund basic research that could translate into operational capability, or to fund the transition of a research product (such as a simulation of a solar eruption, or a model of economic impact) into an operational capability. Similarly NASA and the NSF are well-posed to support cutting edge

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[5] National Research Council. 2013. Solar and Space Physics: A Science for a Technological Society. Washington, DC: The National Academies Press. https://doi.org/10.17226/13060.
[6] The Scientific Foundation of Space Weather, Space Science Reviews (2018), ISSN: 0038-6308 (Print) 1572-9672 (Online).
[7] Fox, N.J., Velli, M.C., Bale, S.D. et al. Space Sci Rev (2016) 204: 7. https://doi.org/10.1007/s11214-015-0211-6
[8] Kasper, J.C., Abiad, R., Austin, G. et al. Space Sci Rev (2016) 204: 131. https://doi.org/10.1007/s11214-015-0206-3

science and technology development, but are generally not in a position to fund the kind of long term monitoring of conditions needed to develop and test forecasting tools. This makes it very difficult for a researcher to develop a new observational capability specifically to improve space weather awareness, or for a modeler or theorist to maintain or extend computer simulations to improve forecasts. One or more agencies must either be given the mandate to foster the transition from research to operations or a managing authority must have the mandate to coordinate this work across agencies.

Our current capability to forecast space weather is decades behind our capability to predict terrestrial weather. This is largely because there are significant aspects of the underlying physics that governs the solar atmosphere and interplanetary space – plasma physics – that we do not sufficiently understand, because our observational view of the connection between the Sun and the Earth is incomplete, and because what we do understand or can predict has not been converted into an operational capability. Over the space age, we have accumulated extensive knowledge of the regions of space surrounding the Earth and the Sun, and the governing physical processes operating in these regions. However, this knowledge, with exceptions, has not fully translated into a systematic operational forecast capability that informs the users of space weather data on timescales sufficient to take appropriate actions, whether for day-to-day operations or to protect against catastrophic events.

What is required is to increase the warning time for when a CME strikes Earth and the probability of it causing a GMD from tens of minutes to at least ten hours for the most extreme events. This would give us time to produce a regional forecast of the resulting GMD and other space weather effects, with sufficient time to make an informed decision whether to take active measures to protect the grid. In order to accomplish this we need (1) new and more capable observations from satellites strategically located to observe the Sun; (2) improved understanding and models that allow us to determine the ambient conditions in the space environment between Sun and Earth and the evolution of CMEs during their transit; (3) improved methods of assimilating the data from the new observations into the models; and (4) improved understanding of the response of the Earth's magnetic field to the impact of a CME to correctly predict the resulting GMD.

Exhibit G

"Electrical Claims and Space Weather: Measuring the visible effects of an invisible force." Zurich Risk Engineering, Lockheed Martin Advanced Technology Center. June 2015.

Electrical Claims and Space Weather

Measuring the visible effects of an invisible force
June 2015
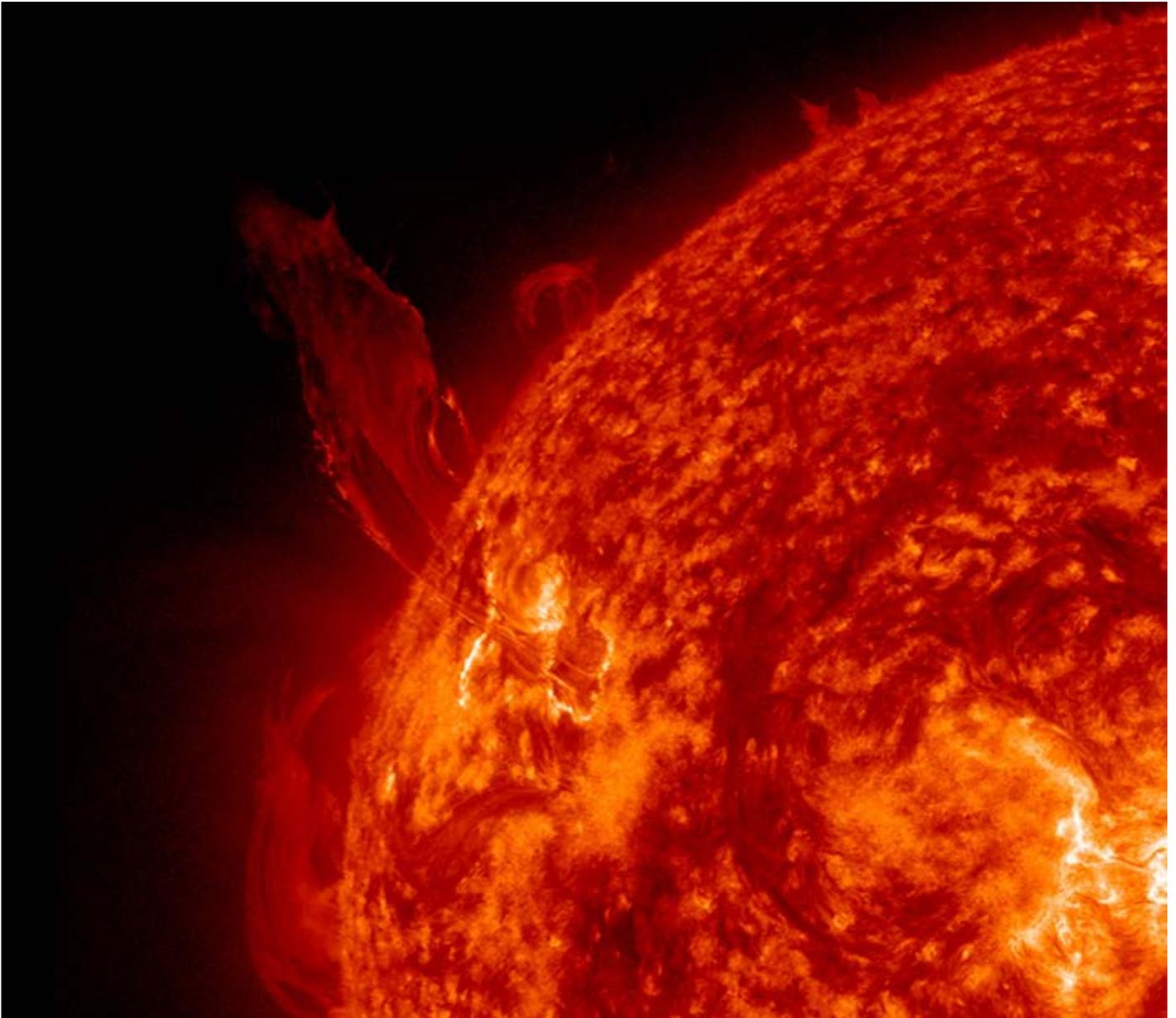
Image Credit: NASA/SDO/Goddard Space Flight Center [1]

Authors:

Robert W. Dobbins – Zurich Risk Engineering [2]

Karel Schriiver – Lockheed Martin Advanced Technology Center [2]

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1. Executive Summary

Property and casualty insurance companies are concerned with many types of risks - fire, flood, wind, equipment breakdown and others that affect businesses and homes. One of the primary functions of an insurance company is to protect their customer against losses. An insurance company will seek to protect their customers' insured property by providing guidance on ways to care for and protect that property. This minimizes the overall risk to both the insured and the insurer.

Over the years insurers have become very familiar with the types of risks and hazards they insure and how to protect the property they cover. They have also learned how much premium to charge to sustain their own business. As science and engineering provide innovations to an ever evolving society, new risks are always emerging. Insurance companies are constantly looking ahead at emerging risks to determine how they will meet new challenges.

Space storms that affect the Earth are by no means new. However, the equipment they can affect and the way this equipment is installed and used today is relatively new and rapidly expanding. What these storms from space can do to this equipment is considered an emerging risk. This risk is being studied by industries, scientists, engineers and political bodies because of the also considerable threat this risk poses to society today.

This risk is being studied by industries, scientists, engineers and political bodies because of the also considerable threat this risk poses to society today.

2. Introduction

2.1 Facing the storm

Superstorm Sandy was a devastating storm to the US eastern seaboard in 2012. The Philippines are still recovering from the effects of Supertyphoon Haiyan in 2013. The effects of Hurricane Katrina and the massive recent tsunamis striking Japan and Indonesia were disastrous. These were all monstrous events that were broadcast minute by minute, hour by hour, on our televisions and computers. Our communication devices brought vivid images of the devastation caused by these storms into our homes and businesses as we watched the results of the cataclysmic forces that nature can bring to bear on our planet.

2.2 A force of nature

There are other forces that can affect our planet in ways that may not make the news. In a paper published by Zurich Risk Engineering, <u>Don't Get Burnt by Solar Storms: What is Your SPF Level?</u>, [4] Zurich Risk Engineering considered the effects of solar storms as a potential emerging threat. The paper was written ahead of the recent solar maximum peak period.

Its intent was to point out the potential damage that geomagnetically induced currents (GIC) produced by the coronal mass ejections (CME) from solar storms can and have done to our interconnected electrical distribution grid networks.

Many in the scientific and electrical-engineering communities fear that our aging and growing electric infrastructure has become much more vulnerable to the effects of CME…

Many in the scientific and electrical-engineering communities fear that our aging and growing electric infrastructure has become much more vulnerable to the effects of CME and the resulting geomagnetically induced currents.

The sun is continuously undergoing nuclear fusion and blows electrified solar gas (plasma) and CME into space. Violent solar storm events occur when the sun's solar magnetic field is strained and suddenly snaps to a new configuration to release massive amounts of energy with intense flashes of light, radiation and CME. Space weather is the term given to violent transfers of matter and energy from the sun to the earth. This type of matter and energy transfer from the sun is often referred to as a "Solar Storm." Although solar storms can occur at any time, their frequency of occurrence and intensity varies on an 11-year cycle (9-14 years cycles) when this activity reaches its maximum activity.

The CME associated with this space weather can have strong embedded magnetic fields. They travel with high velocity and contain atomic particles from the sun, including electrically-charged high-energy atomic particles such as protons and electrons, hydrogen nuclei and large quantities of helium, iron and nickel nuclei. When directed towards the earth, the shock wave of these atomic particles from the CME interacts with earth's magnetic field to generate geomagnetic storms (disturbances) in the earth's magnetic fields. These interactions results in Geomagnetically-Induced Currents (GIC) in many electrical (and mechanical) systems. Spectacular northern and southern lights displays (Aurora Borealis) are the most visible but harmless examples of this phenomenon around the earth's poles. In periods of solar minimums, they are observed in higher latitudes near the North and South Poles but, during periods of solar maximums, they have been observed as far away south as the equatorial regions.

Although all of the effects of solar storms are not fully understood, significant research has occurred over the years to improve our understanding through extensive observations and measurements. The results from this research have also helped to improve scientists' modelling and forecasting abilities, making short and long-term predictions more reliable in the future. It is now believed that GIC in the earth caused by these solar storms can seriously affect the safety and performance of critical infrastructure assets.

Examples include high frequency telecommunication, electrical power grid, space satellites, large pipelines, railway systems, financial systems, GPS navigation and aviation just to name a few. It is believed that an extended interruption to the electrical power grid could cause extreme loss impact at the primary, secondary and tertiary levels including its societal and economic impact.

NASA Photo – See Licensing Statement in Appendix [1]

Advance warnings after observation of initial events of the sun's solar flare activities and prompt precautionary actions have recently helped minimize damage to satellites, electric systems and airlines.

There have already been examples of the type of challenges that space weather can present to our modern infrastructure. Some valuable lessons were learned during the Quebec solar event of 1989, when a space storm caused a large-scale blackout in Canada.

A solar superstorm event lasting from October 22 - November 4, 2003 was another event that raised awareness, and started discussions about needed societal change. This solar storm began to reveal the potential threat to our electrical power grids and related infrastructure supported by electricity. According to the Goddard Space Flight Center, at least eight shock waves from powerful CMEs from our sun impacted earth's magnetic field. During this period billions of tons of electrified solar gas (plasma) struck earth's magnetic field. Although the field keeps the solar gas from reaching earth directly, this CME raised radiation levels in space near earth above dangerous levels for nearly two weeks. [3]

Much has been discussed and written among industry, business and government bodies to discuss the actions that could or should be taken to protect against the potential detrimental effects of this phenomenon.

Much has been written and there have been and continue to be many discussions and meetings among industry, business and government bodies …

3.   Considering the data

Damage to major electrical equipment in the high-voltage network caused by solar storms in the past has recently raised questions about the potential damage to the more mundane electrical equipment used in our everyday lives that is connected to the 110-volt distribution network; solar storms rattle the earth's magnetic field, and that, in turn, drives currents through the long power lines and their transformers that are not always capable of withstanding the GIC. The resulting power surges can also be damaging to a wide variety of electrical devices and components.

3.1   Question of effect

Do these solar forces have an effect on electrical equipment used all around us - equipment like motors? Communications equipment? Air conditioning equipment? Computers and computer servers? Can this equipment be affected by GIC? How can we tell? How often does the damage occur? If this type of damage is occurring, can it be prevented? And how much is it costing the consumer and insurance companies to repair?

Finally, could this be further evidence as to the type of catastrophic damage that a major solar storm could cause to the much larger electrical equipment used in in power grids? These would seem to all be good questions but difficult to answer without data previously unavailable to researchers who have been considering the bigger picture.

3.2   Organizing and assessing

Like other large property and casualty insurers, Zurich Insurance routinely analyzes statistics of insurance in North America. These are claims associated with commercial uses of all insured equipment including electrical and electronic equipment, and consider both the equipment and any resulting loss of productivity. Is there a way to compare the number of electrical losses to periods of increased solar or geomagnetically active periods in the areas where electrical losses occurred?

> Do these solar forces have an effect on electrical equipment used all around us? Can this equipment be affected by geomagnetically induced currents?

After attending the 2012 Electrical Infrastructure Summit in Washington DC and hearing a presentation given by Lockheed Martin, a joint project was suggested by Zurich Risk Engineering.

This project would seek to compare when and how many electrical losses occur with the amount of geomagnetic activity that occurs during active solar periods; an analysis would be performed to determine if electrical losses increased during space storms. Zurich Insurance possesses claims data with usable information dated from 1987 to the present; Lockheed Martin has expertise in analyzing when geomagnetically active periods occurred and the relative strength of solar activity over that time frame.

The research produced some new ideas:

- What effects are solar explosions having on equipment when the storms are not so strong that they cause blackouts but they are strong enough to produce GIC?

- Do space storms affect other types of electrical or electronic equipment besides large transformers and satellites?

- If they do affect other types of equipment, how can it be determined?

These questions were addressed in a joint study entitled, Assessing the Impact of Space Weather on the Electric Power Grid Based on Insurance Claims for Industrial Power Equipment [5] published in the journal *Space Weather* in August, 2014.

3.3   Affected equipment

In the noted study, a statistical analysis of over 11,000 insurance claims submitted from 2000 through 2010 for equipment losses and related business interruptions was performed.

These claims were for losses reported in North American commercial organizations and were associated with damage to, or malfunction of, electrical and electronic equipment. The statistics reflect that typical claim rates are reported at higher frequencies on days when geomagnetic activity is elevated.

See the following chart for an example of what the data show.
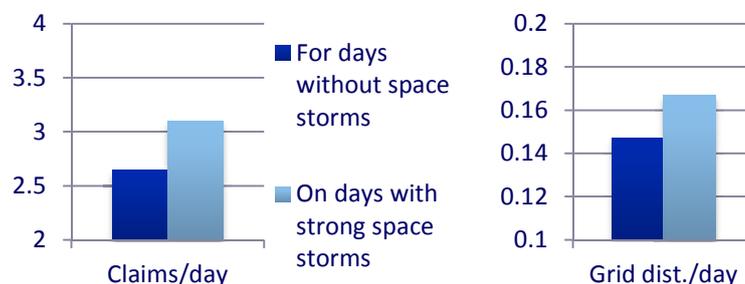
Figure 1. Insurance claims per day for electrical and electronic equipment to Zurich NA (left) [5] and the number of grid disturbances per day (right) [10]. Red bars show the average number of all claims and grid disturbances on the top 10% of most geomagnetically active days, while the blue bars show the numbers for nearby geomagnetically inactive days.

This type of comparison looks to minimize the effects of influences other than space weather – such as ordinary weather, changes in the power-grid, and change in society's use of power – thereby enabling the determination of the impacts of space weather alone.

Claims for damage due to electrical causes increased by approximately 20% for the top 5% of the most geomagnetically active days (i.e. days that have the highest energy levels measured due to impact from space weather). These claims increased by about 10% for the top third of most geomagnetically active days overall.

The study goes on to indicate that the dependence of claims rates for electrical equipment for geomagnetic activity are the same as that of past major disturbances in the US high-voltage electric power grid. When all of the available numbers were presented, there is not only a risk to the more advanced parts of national electrical grids and satellites but the effects of space weather appear to have some direct bearing on electrical equipment that we have all around us including computer servers, telecommunications equipment, generators, motors and many other types of electrical equipment.

The study concluded that there is a significant increase in claim frequencies when there is an increase in geomagnetic activity; an increase that is comparable in magnitude to the increase in occurrence of frequencies of space weather-related phenomenon.

3.4   Data effectiveness

For this study, Senior Vice President of Zurich Machinery Breakdown, Cass Kuhlke, Zurich North America, estimates that Zurich's market share for the study period was about 8% in North America for policies covering commercially-used electrical and electronic equipment and business interruptions related to failures(5). The full sample of Zurich claims for the study used 11,242 entries that were related to electric or electronic failures over the study period 2000 to 2010.

If Zurich Insurance insured 8% of the Equipment Breakdown market during this time period, then there may have been some 140,000 electrical claims in North America that could have been examined in a similar study if all insurance companies could provide similar data. If claims increase by 20% on the most geomagnetically active days and increase by about 10% for the top third of most geomagnetically active days overall, we can only surmise how much this may be costing industry and insurers overall in an 11 year period. The amount would have to be considerable.

The Zurich Insurance-Lockheed Martin joint study explains fully how the claims data was compared to geomagnetic current data during this time period to arrive at the above conclusions. This study could lead to other questions:

- Is 8% of the market a fair representation of the entire market?

- Can we derive overall costs from this data?

- Does the damage occur due to geomagnetically induced current or from previous damage and geomagnetically induced current?

> These costs are related to real numbers occurring in real time for real equipment. The question from an insurance perspective is can steps be taken to help lower those numbers …

The increased damage during times of increased solar activity cannot just be ignored. These are costs related to real numbers occurring in real time for real equipment. Can steps be taken to prevent the losses or damage from occurring?

4. Dollars and data

There were specific costs associated with the claims figures from the Zurich Insurance-Lockheed Martin Study. Zurich Insurance and its affiliated companies paid out millions of dollars in claims over this 11-year period. Likewise, the owners of the equipment paid out funds in the form of insurance deductibles, amounts they had to pay towards equipment repairs prior to insurance remunerations. The costs associated with the non-reimbursed impacts of space storms appear to be very much larger than the insured assets.

4.1   Extrapolating the data

First, let us look at the insurance impact alone. The initial study could only consider claims for property damage and business interruption because the amounts of deductibles that customers paid towards the total amounts were not available for the calucations made. However, we can make some educated deductions along the following lines.

We can estimate that the average deductible for these types of property and casualty losses is 10% of the payment being made by the insurance company. During this time period, Zurich paid out approximately USD 175 million for the electrical losses used in the case study.

Using our assumption that deductibles over the period averaged 10% per loss this would bring the total amount of deductibles paid over the period to about USD 17.5 million. That would bring the total payout by Zurich and its insureds to USD 192.5 million for the period.

We also felt it would be interesting to note the average cost of these claims to the insurance company. Using the initial total number of unfiltered claims in the case study of 11,242, the average amount spent per electrical claim is USD 17,123 each.

When we examine the 8,151 "filtered" claims related to purely electrical issues only (excluding, for example, lightning, theft, flooding, fires, etc.), the amount paid out by Zurich and its insureds totals about USD 151.7 million. The average amount per claim increases to about USD 18,611 each. The types of claims reported range from damage to thermostats, phones and small motors to large motors, generators and transformers. All types of equipment are included in the survey.

The costs associated with the non-reimbursed impacts of space storms appear to be very much larger than the insured assets.

4.2   Claim payouts

Assuming Zurich held 8% of the US market during the period and our customers incurred USD 151.7 million for electrical claims associated with solar storms, it is then estimated that total losses incurred would have been about USD 1.9 billion for the entire US market over the ten year period.

The aforementioned case study concludes that the overall fraction of all insurance claims statistically associated with the effects of geomagnetic activity is 4%. This would indicate a total payout in the US only over that time period for "normal" electrical equipment related to GIC to be about USD 7.6 million annually to all insurance companies and industries.

But this does not include the costs associated with business interruptions and lost time caused by the damaged equipment. Information is available, however, that allows us to make an estimate of the overall impact.

4.3   Overall cost to the national economy

Until now, we looked at costs only to pay for damage to equipment that was insured by one insurance company in one region of the globe and some of the business interruption costs associated with that damage when covered by an insurance policy. These costs, however, do not begin to cover the amount of anticipated losses that occur during major power outages or that would occur with a complete breakdown of the US power grid. For an idea of those types of losses, we would turn to a review of the EPRI-funded study of power-quality impacts on the US economy "The Cost of Power Disturbances to industrial & Digital Economy Companies" [6] and an equivalent one for the European Union countries(9).

These studies suggest that the real cost to society of electrical problems associated with space storms by far exceeds what we see in the Zurich Insurance-Lockheed Martin "snapshot of time" claims payouts results. It is hard to quantify that impact with certainty, but we can make estimates based on studies of the impacts of all power quality variations on the economy, and then taking the percentage attributable to space weather assuming that these are not substantially different in their impacts from all other issues that affect electic power supply.

One such study [6] for the US asked companies around the country to estimate the impacts of all power outages and power quality issues (that include voltage sags, frequency drifts, transient perturbations, and harmonics besides that standard 60 Hz voltage cycle) on their business. The estimate would include not only equipment damage, but also loss of productivity, loss of materials, problems with resumption of production, or any other impact. The study then estimated the overall impact based on the thousand respondents that participated in their survey. When correcting for inflation from 2000 to the present, the overall economic impact from power perturbations was as large as USD140 billion per year to USD230 billion per year. Another (much smaller) study [9] for 25 members states of the European Union estimated an economic impact (converted to dollars and corrected for inflation from 2007 to the present) upwards of USD200 billion per year.

… we are potentially looking at an average impact on the order of US$10 Billion per year each for both the US and European economies!

If we consider again the results of the Zurich Insurance-Lockheed Martin Study and conclude, conservatively, that space weather is associated with some 4% of all of these impacts, we are potentially looking at an average impact on the order of USD10 billion per year each for both the overall US and European economies!

These numbers are rather uncertain because they are determined by relatively small surveys of industry and assume that space weather impacts are on average comparable to the impacts of any other issue with the continuity of stable power supplies. But we learn three important things from this:

1. Overall economic impacts of space weather on only electric power supply are worth paying attention to,

2. The existence of such impacts lets us begin to study what might happen if the Sun generated even larger storms,

3. The loss of insured hardware is only a very small fraction of the overall losses to industry through the interruption of their regular operations.

5.   Using the data

After examining the hazard and risks associated with solar storms, the data used to examine the risk, the effectiveness of that data, the type of equipment affected and the dollar amounts that could be at stake, the question becomes, what do we do with this information? Can it help make a difference in how our society prepares for such an event?

5.1   Assumed costs versus probable costs

Over ten years, USD 1.9 billion may not sound like much to the property and casualty insurance industry, when compared to all claims paid during that time, but there are other factors to consider. These are the probable known costs through insured property. The total damage being caused to businesses is much higher through uninsured or unclaimed damage, business interruptions and productivity losses. Why suffer these types of losses when actions can be taken to reduce them? There are ways to protect equipment against this type of harmful electrical current.

Our study only considered claims in one small sector of one company – Equipment Breakdown for Zurich Insurance covers 8% of the equipment breakdown market. It is suspected that there are untold thousands of claims under other business segments, primarily property insurance coverage, that are listed as fire or explosion that could have very well been caused by damage related to overheating due to the effects of GIC.

That is one of the difficulties of studying the effects of damage from space weather – much of the damage occurs over time and is cumulative.

Damage from space weather is also occurring concurrent with the normal "runtime" damage that occurs when operating any type of mechanical/electrical equipment over a period of time. When the equipment finally does break down, it can be very difficult to determine if the initiating cause of breakdown was from GIC from space weather or just overheating from long use, poor maintenance or some other mechanical issue.

There is a considerable cost to protect against the effect of geomagnetically induced currents or electro-magnetic pulses.

Finally, bringing the scientific community and industry together on this matter is proving to be somewhat problematic.

Scientists have the evidence and the facts; indeed, even history appears to agree that our planet will eventually be subjected to a possibly crippling solar event sometime in the relatively near future.

5.2   Waiting, watching, thinking

The "Big One" has not occurred in modern times – not yet. An entire Canadian provincial electrical grid was knocked offline in 1989 for fourteen hours but they recovered quickly and no major property damage was experienced. There was several million dollars in business income lost and many frayed nerves but the province persevered and learned much.

South Africa lost 14 of its 400 kV transformers over a two-week period during a drawn-out solar event in 2003 – a major inconvenience to an entire country for a few days and parts of the country for months but they did manage to endure and recover from that episode as well.

Nothing like the worst known historical case – the Carrington Event of 1859 – has occurred and caused damage to our modern-day electrical infrastructure. However, many scientists believe an event like this one could dwarf the more recent moderate solar events and cause catastrophic damage to whatever part of the globe is directly affected.

The issue in trying to decide to take steps to protect our electrical equipment from this type of hazard appears to be overall cost. There is a considerable cost to protect against the effect of GIC or electromagnetic pulses. Protective devices such as surge suppression protection has been developed and tested that can protect all types of electrical equipment against these types of damaging electrical currents but there can be substantial costs to retrofitting existing equipment with the devices they need for protection.

Adding the protection during manufacturing also adds cost to the construction of the equipment. If one manufacturer adds the device and has to raise the price to maintain profit levels while another manufacturer decides to not add the device and continue to sell the equipment at the original price, inequities develop in the market and unprotected devices will most likely continue to be installed.

If an insurance company decided to recommend to their customers that the protective devices be installed to protect their investment on critical equipment or raise the premiums on that equipment, many customers may simply move to other insurance companies that did not recommend such a requirement. This can occur when such protective equipment is not mandated by construction codes or laws.

As described in a 2013 AON Benfield report on geomagnetic storms (AON Benfield, January 2013)[7], it would be very difficult for insurance companies to try to price this type of risk for several reasons:

- Most risk professionals do not have a complete understanding of the technical complexities of this hazard and the vulnerability of the components of equipment to geomagnetically induced currents

- There is no industry-wide definition of an industry-wide loss occurrence from extreme space weather that has caused a large scale economic and social disruption and recovery issue on insurance policies

- The majority of direct and contingent business interruption contracts still depend on the loss of use of property due to physical damage

- The material damage and replacement costs from the solar event would be a small component of the total losses with the nature of the larger losses being potentially much more exotic due to the cause of damage

6.   Decisions

6.1   Where to begin

It would appear then that all stakeholders are at an impasse – industry, government, science, insurance and society in general. Each group is aware that the hazard exists; solar storms occur routinely and cyclically. Each group knows that strong solar storms can cause damage to our electrical equipment and, as shown by the recent Zurich Insurance-Lockheed Martin Study, the damage occurs to all kinds of electrical equipment, not just large transformers and power grids.

We know that a very strong storm directly affects the earth about once every 150 to 200 years so our planet may be due for the next one; a storm strong enough to allow people to be able to see the Aurora Borealis near the equator like they did in 1859; a storm strong enough to set equipment attached to electrical lines on fire much like what happened to telegraph lines in use at the time.

It is fairly certain that this type of event will happen again; not maybe, not might, but will; solar storms are a natural reoccurring activity of our solar system's sun and this planet will be affected in some manner.

> … solar storms are a natural reoccurring activity of our solar system's sun and this planet will be affected in some manner.

Recovery from another Carrington-type event could take a very long time.

Step-down Transformer (Photo by Zurich RE Pat Dunphy – 20131022)

The primary stakeholders in this discussion know that the equipment a modern society depends on can be protected from the effects of this phenomenon. The US grid can be protected by the installation of surge suppressors in strategic equipment. These same groups also know that it would cost taxpayers and industry a great deal of money to make these changes.

The way to mandate that protective equipment be installed would be to pass laws that institute rules to require those changes. The only way to see such laws passed, however, would be to have enough people understand the consequences of not passing them, what the potential costs can be if such a superstorm occurs and the at-risk equipment and systems are not protected.

Many of these stakeholders know how long it takes to replace a 500 kV transformer – the kind you find in our electric power grid. It can take up to 12 to 18 months to replace one of these large transformers because they are no longer built in large quantities in the United States. Is it even possible to imagine trying to replace 200 of these transformers after a major solar storm event? This issue alone might make it possible to contemplate why such an event could dwarf an event like Superstorm Sandy or Hurricane Katrina. When we now consider how much damage is believed to have been caused or is being caused by normal solar cycles, it may be almost impossible to imagine the amount of damage that could occur to all of the types of electrical equipment in use in our everyday lives. Recovery from another Carrington-type event could take a very long time.

6.2 The debate

There are many facts known about the effects of space weather and discussions continue. The known facts are discussed and theories debated in industry and manufacturing offices, at utility offices and power plants, by scientists and engineers and even in the Halls of Congress in the US and the House of Commons in the UK. Many scientists and engineers discuss ways to monitor the sun and measure the solar cycles so they can detect the strength of the solar waves and resulting coronal mass ejections that could possibly hit the earth. Insurance companies debate whether this type of damage would be a covered loss or not.

If it was excluded from policies, how could it be proven the damage came from GIC when the damage looks like any other kind of electrical system damage?

7. Conclusion

We live in an interconnected world.

Photo authorized by Smithfield Foods, Inc. - 20100409

We live in an interconnected world. It now appears that our power grids are not the only equipment at risk here during solar-driven space storms; much of the electrical equipment we use in our everyday lives appears to be at some risk of damage from a major solar event. Regardless of what part of the planet is most affected by the next major solar event, those effects will most likely be felt around the globe in one way or another. If we understand the technical aspects of this threat and interconnected vulnerabilities in various industry segments, such as power distribution, electric utilities, oil and gas pipelines in the energy sector and technology exposures, then this issue could become a top risk management priority. It could also become a national defense and homeland readiness issue due to the damage such a storm could inflict on a country's electrical infrastructure and society.

The world doesn't have to wait for the worst to happen. Studies by other insurance companies have been published, scientists and politicians from around the planet have been sounding an alarm in their respective countries and studies like the one recently published by Lockheed Martin and Zurich Insurance continue to add more information to the ever increasing evidence of this threat. What comes next?

Is it possible to follow up on all of these studies and warnings with a joint effort? Can there be an assessment of our nations' leaders' awareness of this threat, readiness, prioritization of their mitigation strategies and action plans? This would require continuing the high-level dialog with a variety of stakeholders and participation in workshops and other forums.

Studies of protective equipment must be continued with testing on installed equipment to occur that proves the theories our engineers and scientists tell us about. The world can prepare for another Carrington event because the technology and the know-how are available. Perhaps insurance companies can provide some incentives for those that take on the burden of these tests in a partnership-type arrangement since we are protecting both of our interests.

We have knowledge and it appears we have been warned. The question is – do we have the will to follow through on that knowledge?

> Regardless of what part of the planet is most affected by the next major solar event, those effects will most likely be felt around the globe in one way or another.

8.   Glossary

Carrington Event: A powerful geomagnetic solar storm in 1859 during solar cycle 10. A set of solar coronal mass ejections interacted with Earth's magnetosphere and induced one of the largest geomagnetic storms on record. The associated "white light flare" in the solar photosphere was observed and recorded independently by English astronomers Richard C. Carrington and Richard Hodgson.

Coronal Mass Ejection (CME): Large eruption of magnetized plasma from the Sun's outer atmosphere, or corona, that propagates outward into interplanetary space. The CME is one of the main transient features of the Sun. Although it is known to be formed by explosive reconfigurations of solar magnetic fields through the process of magnetic reconnection, its exact formation mechanism is not yet understood.

Geomagnetically Induced Current (GIC): A manifestation at ground level of space weather. During space weather events, electric currents in the magnetosphere and ionosphere experience large variations, which manifest also in the Earth's magnetic field. These variations induce currents (GIC) in conductors operated on the surface of Earth. Electric transmission grids and buried pipelines are common examples of such conductor systems. GIC can cause problems, such as increased corrosion of pipeline steel and damaged high-voltage power transformers. GIC are one possible consequence of geomagnetic storms, which may also affect geophysical exploration surveys and oil and gas drilling operations.

Electromagnetic Pulse (EMP): A broadband, high-intensity, short-duration burst of electromagnetic energy. Such a pulse may originate from the electromagnetic radiation from a nuclear explosion caused by Compton-recoil electrons and photoelectrons from photons scattered in the materials of the nuclear device or in a surrounding medium. The resulting electric and magnetic fields may couple with electrical/electronic systems to produce damaging current and voltage surges. May also be caused by nonnuclear means such as from the CME produced during a solar space storm

Power Grid: A system of high-voltage cables and transformers by which electrical power is distributed throughout a region

Solar Storm: a sudden temporary outburst of energy from a small area of the sun's surface —manifesting as either a solar flare or coronal mass ejection, or often both.

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Exhibit H

"Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment."
C. J. Schrijver, R. Dobbins, W. Murtagh, and S. M. Petrinec. July 8, 2014.

Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment

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Abstract Geomagnetically induced currents are known to induce disturbances in the electric power grid. Here we perform a statistical analysis of 11,242 insurance claims from 2000 through 2010 for equipment losses and related business interruptions in North American commercial organizations that are associated with damage to, or malfunction of, electrical and electronic equipment. We find that claim rates are elevated on days with elevated geomagnetic activity by approximately 20% for the top 5% and by about 10% for the top third of most active days ranked by daily maximum variability of the geomagnetic field. When focusing on the claims explicitly attributed to electrical surges (amounting to more than half the total sample), we find that the dependence of claim rates on geomagnetic activity mirrors that of major disturbances in the U.S. high-voltage electric power grid. The claim statistics thus reveal that large-scale geomagnetic variability couples into the low-voltage power distribution network and that related power-quality variations can cause malfunctions and failures in electrical and electronic devices that, in turn, lead to an estimated 500 claims per average year within North America. We discuss the possible magnitude of the full economic impact associated with quality variations in electrical power associated with space weather.

1. Introduction

Large explosions that expel hot, magnetized gases on the Sun can, should they eventually envelop Earth, effect severe disturbances in the geomagnetic field. These, in turn, cause geomagnetically induced currents (GICs) to run through the surface layers of the Earth and through conducting infrastructures in and on these, including the electrical power grids. The storm-related GICs run on a background of daily variations associated with solar (X)(E)UV irradiation that itself is variable through its dependence on both quiescent and flaring processes.

The strongest GIC events are known to have impacted the power grid on occasion [see, e.g., *Kappenman et al.*, 1997; *Boteler et al.*, 1998; *Arslan Erinmez et al.*, 2002; *Kappenman*, 2005; *Wik et al.*, 2009]. Among the best known of such impacts is the 1989 Hydro-Québec blackout [e.g., *Bolduc*, 2002; *Béland and Small*, 2004]. Impacts are likely strongest at middle to high geomagnetic latitudes, but low-latitude regions also appear susceptible [*Gaunt*, 2013].

The potential for severe impacts on the high-voltage power grid and thereby on society that depends on it has been assessed in studies by government, academic, and insurance industry working groups [e.g., *Space Studies Board*, 2008; *FEMA and NOAA*, 2010; *Kappenman*, 2010; *Hapgood*, 2011; *JASON*, 2011]. How costly such potential major grid failures would be remains to be determined, but impacts of many billions of dollars have been suggested [e.g., *Space Studies Board*, 2008; *JASON*, 2011].

Noncatastrophic GIC effects on the high-voltage electrical grid percolate into financial consequences for the power market [*Forbes and St. Cyr*, 2004, 2008, 2010] leading to price variations on the bulk electrical power market on the order of a few percent [*Forbes and St. Cyr*, 2004].

Schrijver and Mitchell [2013] quantified the susceptibility of the U.S. high-voltage power grid to severe, yet not extreme, space storms, leading to power outages and power-quality variations related to voltage sags and frequency changes. They find, "with more than 3σ significance, that approximately 4% of the

disturbances in the U.S. power grid reported to the U.S. Department of Energy are attributable to strong geomagnetic activity and its associated geomagnetically induced currents."

The effects of GICs on the high-voltage power grid can, in turn, affect the low-voltage distribution networks and, in principle, might impact electrical and electronic systems of users of those regional and local networks. A first indication that this does indeed happen was reported on in association with tests conducted by the Idaho National Laboratory (INL) and the Defense Threat Reduction Agency (DTRA). They reported [*Wise and Benjamin*, 2013] that "INL and DTRA used the lab's unique power grid and a pair of 138kV core form, 2 winding substation transformers, which had been in-service at INL since the 1950s, to perform the first full-scale testing to replicate conditions electric utilities could experience from geomagnetic disturbances." In these experiments, the researchers could study how the artificial GIC-like currents resulted in harmonics on the power lines that can affect the power transmission and distribution equipment. These "tests demonstrated that geomagnetic-induced harmonics are strong enough to penetrate many power line filters and cause temporary resets to computer power supplies and disruption to electronic equipment, such as uninterruptible power supplies."

In parallel to that experiment, we collected information on insurance claims submitted to Zurich North America (NA) for damage to, or outages of, electrical and electronic systems from all types of industries for a comparison with geomagnetic variability. Here we report on the results of a retrospective cohort exposure analysis of the impact of geomagnetic variability on the frequency of insurance claims. In this analysis, we contrast insurance claim frequencies on "high-exposure" dates (i.e., dates of high geomagnetic activity) with a control sample of "low-exposure" dates (i.e., dates with essentially quiescent space weather conditions), carefully matching each high-exposure date to a control sample nearby in time so that we may assume no systematic changes in conditions other than space weather occurred between the exposure dates and their controls (thus compensating for seasonal weather changes and other trends and cycles).

For comparison purposes, we repeat the analysis of the frequency of disturbances in the high-voltage electrical power grid as performed by *Schrijver and Mitchell* [2013] for the same date range and with matching criteria for threshold setting and for the selection of the control samples. In section 2 we describe the insurance claim data, the metric of geomagnetic variability used, and the grid-disturbance information. The procedure to test for any impacts of space weather on insurance claims and the high-voltage power grid is presented and applied in section 3. We summarize our conclusions in section 4 where we also discuss the challenges in translating the statistics on claims and disturbances into an economic impact.

2. Data

2.1. Insurance Claim Data

We compiled a list of all insurance claims filed by commercial organizations to Zurich NA relating to costs incurred for electrical and electronic systems for the 11 year interval from 1 January 2000 through 31 December 2010. Available for our study were the date of the event to which the claim referred, the state or province within which the event occurred, a brief description of the affected equipment, and a top-level assessment of the probable cause. Information that might lead to identification of the insured parties was not disclosed.

Zurich NA estimates that it has a market share of approximately 8% in North America for policies covering commercially used electrical and electronic equipment and contingency business interruptions related to their failure to function properly during the study period. Using that information as a multiplier suggests that overall some 12,800 claims are filed per average year related to electrical/electronic equipment problems in North American businesses. The data available for this study cannot reveal impacts on uninsured or self-insured organizations or impacts in events of which the costs fall below the policy deductible.

The 11 year period under study has the same duration as that characteristic of the solar magnetic activity cycle. Figure 1 shows that the start of this period coincides with the maximum in the annual sunspot number for 2000, followed by a decline into an extended minimum period in 2008 and 2009, ending with the rise of sunspot number into the start of the next cycle.

The full sample of claims, regardless of attribution, for which an electrical or electronic system was involved includes 11,242 entries. We refer to this complete set as set *A*.
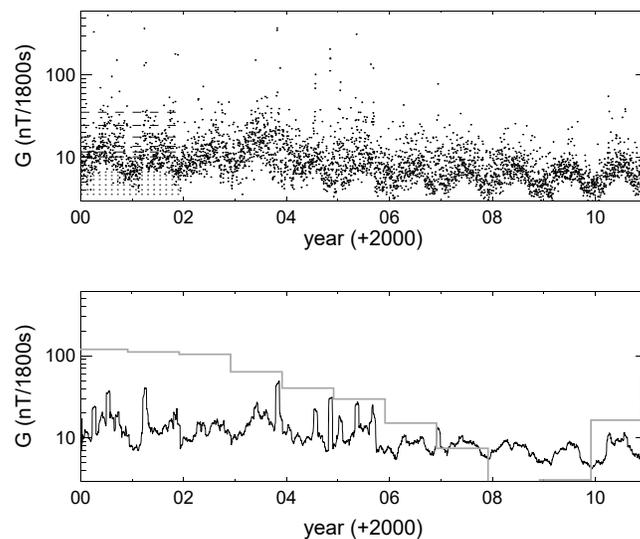
Figure 1. (top) Daily values $G \equiv \max(|dB/dt|)$ based on 30 min intervals (dots; nT/1800s) characterizing geomagnetic variability for the contiguous United States versus time (in years since 2000). The 27 day running mean is shown by the solid line in the bottom panel. The levels for the 98, 95, 90, 82, 75, and 67 percentiles of the entire sample are shown by dashed lines (sorting downward from the top value of G) and dotted lines (sorting upward from the minimum value of the daily geomagnetic variability as expressed by $G \equiv \max(|dB/dt|)$). (bottom) The grey histogram shows the annual mean sunspot number.

Claims that were attributed to causes that were in all likelihood not associated with space weather phenomena were deleted from set A to form set B (with 8151 entries remaining after review of the Accident Narrative description of each line item). Such omitted claims included attributions to water leaks and flooding, stolen or lost equipment, vandalism or other intentional damage, vehicle damage or vehicular accidents, animal intrusions (raccoons, squirrels, birds, etc.), obvious mechanical damage, and obvious weather damage (ice storm damage, hurricane/windstorm damage, etc.). The probable causes for the events making up set B were limited to the following categories (sorted by the occurrence frequency, given in percent): Misc: Electrical surge (59%); Apparatus, Miscellaneous Electrical - Breaking (30%); Apparatus, Miscellaneous Electrical - Arcing (4.1%); Electronics - Breaking (1.6%); Apparatus, Miscellaneous Electrical - Overheating (1.4%); Transformers - Arcing (0.9%); Electronics - Arcing (0.6%); Transformers - Breaking (0.5%); Generators - Breaking (0.4%); Apparatus, Electronics - Overheating (0.3%); Generators - Arcing (0.2%); Generators - Overheating (0.2%); and Transformers - Overheating (0.1%).

Figure 2 shows the number of claims received as a function of the mean geomagnetic latitude for the state within which the claim was recorded. Based on this histogram, we divided the claims into categories of comparable size for high and low geomagnetic latitudes along a separation at 49.°5 north geomagnetic latitude to enable testing for a dependence on proximity to the auroral zones. We note that we do not have access to information about the latitudinal distribution of insured assets, only on the claims received. Hence, we can
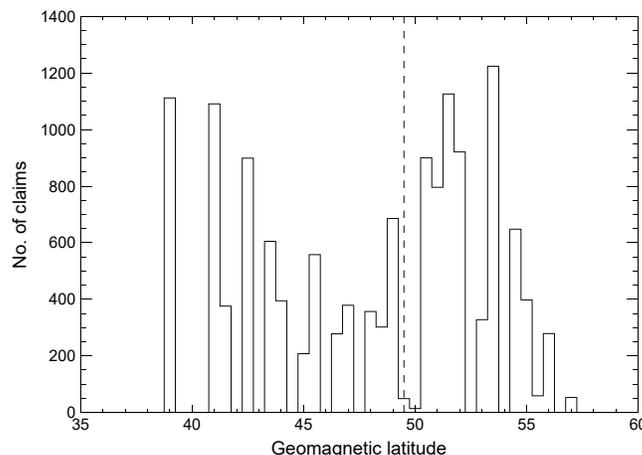
Figure 2. Number of insurance claims sorted by geomagnetic latitude (using the central geographical location of the state) in 0.5° bins. The dashed line at 49.5° is near the median geomagnetic latitude of the sample (at 49.3°), separating what this paper refers to as high latitude from low-latitude states.

only assess any dependence of insurance claims on latitude in a relative sense, comparing excess relative claim frequencies for claims above and below the median geomagnetic latitudes, as discussed in section 3.

2.2. Geomagnetic Data
Geomagnetically induced currents are driven by changes in the geomagnetic field. These changes are caused by the interaction of the variable, magnetized solar wind with the geomagnetic field and by the insolation of Earth's atmosphere that varies globally with solar activity and locally owing to the Earth's daily rotation and annual revolution in its orbit around the Sun. A variety of geomagnetic activity indices is available to characterize geomagnetic field
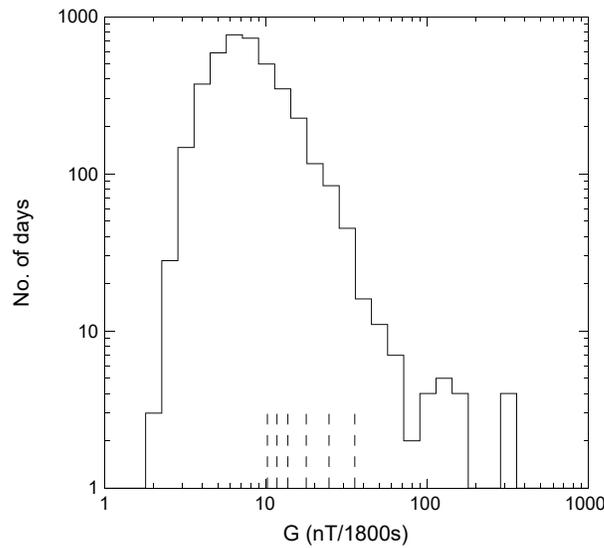
Figure 3. Histogram of the number of days between 1 January 2000 and 31 December 2010 with values of $G \equiv \max(|dB/dt|)$ in logarithmically spaced intervals as shown on the horizontal axis. The 98, 95, 90, 82, 75, and 67 percentiles (ranking G from low to high) are shown by dashed lines.

variability [e.g., *Jursa*, 1985]. These indices are sensitive to different aspects of the variable geomagnetic-ionospheric current systems as they may differentially filter or weight storm-time variations (*Dst*), disturbance-daily variations (Ds), or solar quiet daily variations (known as the *Sq* field), and may weight differentially by (geomagnetic) latitude. Here we are interested not in any particular driver of changes in the geomagnetic field but rather need a metric of the rate of change in the strength of the surface magnetic field as that is the primary driver of geomagnetically induced currents.

To quantify the variability in the geomagnetic field, we use the same metric as *Schrijver and Mitchell* [2013] based on the minute-by-minute geomagnetic field measurements from the Boulder (BOU) and Fredericksburg (FRD) stations (available via http://ottawa.intermagnet.org): we use these measurements to compute

the daily maximum value, G, of $|dB/dt|$ over 30 min intervals, using the mean value for the two stations. We selected this metric recognizing a need to use a more regional metric than the often-used global metrics but also recognizing that the available geomagnetic and insurance claim data have poor geographical resolution so that a focus on a metric responsive to relatively low-order geomagnetic variability was appropriate.

We chose a time base short enough to be sensitive to rapid changes in the geomagnetic field but long enough that it is also sensitive to sustained changes over the course of over some tens of minutes. For the purpose of this study, we chose to use a single metric of geomagnetic variability, but with the conclusion of our pilot study revealing a dependence of damage to electrical and electronic equipment on space weather conditions, a multiparameter follow up study is clearly warranted, ideally also with more information on insurance claims, than could be achieved with what we have access to for this exploratory study.

Figure 4. Normalized histograms of the local times for which the values of $G \equiv \max(|dB/dt|)$ reach their daily maximum: (top) Boulder and (bottom) Fredericksburg. The solid histogram shows the distribution for daily peaks for all dates with G values in the lower half of the distribution, i.e., for generally quiescent conditions. The dotted, dashed, and dash-dotted histograms show the distributions for dates with high G values, for thresholds set at the 95, 82, and 67 percentiles of the set of values for G, respectively.

The BOU and FRD stations are located along the central latitudinal axis of the U.S. The averaging of their measurements somewhat emphasizes the eastern U.S. as do the grid and population that uses that. Because the insurance claims use dates based on local time we compute the daily G

Insurance claims compared to geomagnetic activity

Period 2000/01/01 - 2010/12/31

◇ All claims on geomagnetically active days
✕ All claims on nearby geomagn. inactive days
◇ Surge claims on geomagnetically active days
✕ Surge claims on nearby geomagn. inactive days
☐ Grid disturb. on geomagnetically active days (x10)
△ Grid disturb. on nearby geomagn. inactive days (x10)

Insurance claims compared to geomagnetic activity

Period 2000/01/01 - 2010/12/31

◇ All claims on geomagnetically active days
✕ All claims on nearby geomagn. inactive days
◇ Surge claims on geomagnetically active days
✕ Surge claims on nearby geomagn. inactive days
☐ Grid disturb. on geomagnetically active days (x10)
△ Grid disturb. on nearby geomagn. inactive days (x10)

Figure 5. (top) Claims per day for the full sample of insurance claims (set A) and (bottom) for the sample from which claims likely unrelated to any space weather influence have been removed (set B). Each panel shows mean incident claim frequencies $n_i \pm \sigma_c$ (diamonds) for the most geomagnetically active dates, specifically for the 98, 95, 90, 82, 75, and 67 percentiles of the distribution of daily values of $G \equiv \max(|dB/dt|)$ sorted from low to high (shown with slight horizontal offsets to avoid overlap in the symbols and bars showing the standard deviations for the mean values). The asterisks show the associated claim frequencies $n_c \pm \sigma_c$, for the control samples. The panels also show the frequencies of reported high-voltage power grid disturbances (diamonds and triangles for geomagnetically active dates and for control dates, respectively), multiplied by 10 for easier comparison, using the same exposure-control sampling and applied to the same date range as that used for the insurance claims.

values based on date boundaries of U.S. central time. Figure 3 shows the distribution of values of G, while also showing the levels of the percentiles for the rank-sorted value of G used as threshold values for a series of subsamples in the following sections.

Figure 4 shows the local times at which the maximum variations in the geomagnetic field occur during 30 min intervals. The most pronounced peak in the distribution for geomagnetically quiet days (solid histogram) occurs around 7–8 o'clock local time, i.e., a few hours after sunrise, and a second peak occurs around local noon. The histograms for the subsets of geomagnetically active days for which G values exceed thresholds set at 67, 82, and 95 percentiles of the sample are much broader, even more so for the Boulder station than for the Fredericksburg station. From the perspective of the present study, it is important to note that the majority of the peak times for our metric of geomagnetic variability occurs within the economically most active window from 7 to 18 hours local time; for example, at the 82 percentile of geomagnetic variability in G, 54% and 77% of the peak variability occur in that time span for Boulder and Fredericksburg, respectively.

From a general physics perspective, we note that periods of markedly enhanced geomagnetic activity ride on top of a daily background variation of the ionospheric current systems (largely associated with the "solar quiet" modulations, referred to as the Sq field) that is induced to a large extent by solar irradiation of the atmosphere of the rotating Earth, including the variable coronal components associated with active-region gradual evolution and impulsive solar flaring. We do not attempt to separate the impacts of these drivers in this study, both because we do not have informa-

tion on the local times for which the problems occurred that lead to the insurance claims and because the power grid is sensitive to the total variability in the geomagnetic field regardless of cause.

The daily G values are shown versus time in Figure 1, along with a 27 day running mean and (as a grey histogram) the yearly sunspot number. As expected, the G value shows strong upward excursions particularly
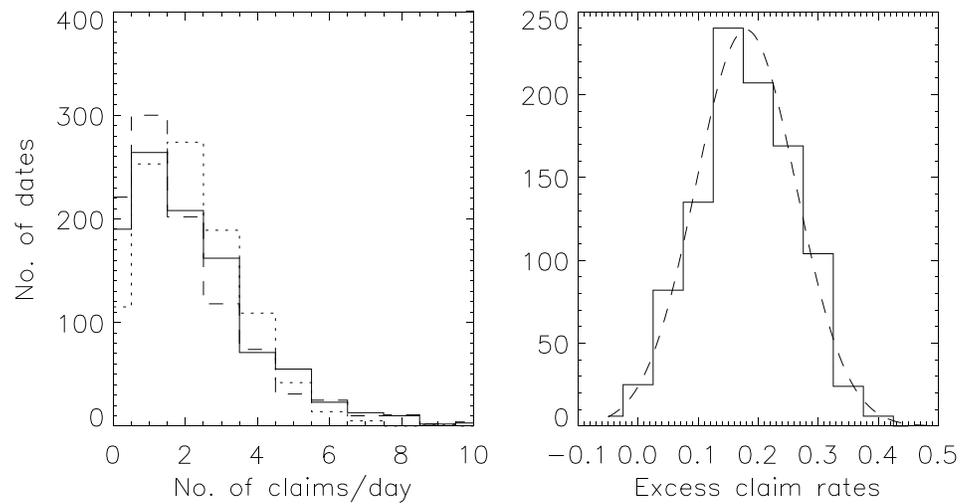
Figure 6. (left) Distribution of the number of claims per geomagnetically active day for set *B* for the top 25% of *G* values (solid) compared to that for the distribution of control dates (divided by 3 to yield the same total number of dates; dashed). For comparison, the expected histogram for a random Poisson distribution with the same mean as that for the geomagnetically active days is also shown (dotted). (right) Distribution (solid) of excess daily claim frequencies during geomagnetically active days (defined as in Figure 6 (left)) over those on control dates determined by repeated random sampling from the observations (known as the bootstrap method), compared to a Gaussian distribution (dashed) with the same mean and standard deviation.

during the sunspot maximum. Note the annual modulation in *G* with generally lower values in the northern hemispheric winter months than in the summer months.

2.3. Power Grid Disturbances

In parallel to the analysis of the insurance claim statistics, we also analyze the frequencies of disturbances in the U.S. high-voltage power grid. *Schrijver and Mitchell* [2013] compiled a list of "system disturbances" published by the North American Electric Reliability Corporation (NERC: available since 1992) and by the Office
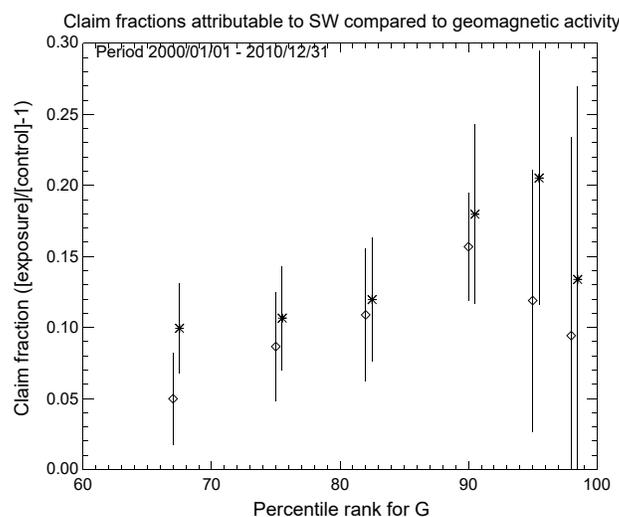
Figure 7. Relative excess claim frequencies statistically associated with geomagnetic activity (difference between claim frequencies on geomagnetically active dates and the frequencies on control dates as shown in Figure 5, i.e., $(n_i - n_c)/n_c$ for the full sample (*A*; diamonds) and for the sample (*B*; asterisks) from which claims were removed attributable to apparently nonspace weather-related causes.

of Electricity Delivery and Energy Reliability of the Department of Energy (DOE; available since 2000). This information is compiled by NERC for a region with over 300 million electric power customers throughout the USA and in Ontario and New Brunswick in Canada, connected by more than 340,000 km of high-voltage transmission lines delivering power generated in some 18,000 power plants within the U.S. [*JASON*, 2011]. The reported disturbances include, among others, "electric service interruptions, voltage reductions, acts of sabotage, unusual occurrences that can affect the reliability of the bulk electric systems, and fuel problems." We use the complete set of disturbances reported from 1 January 2000 through 31 December 2010 regardless of attributed cause. We refer to *Schrijver and Mitchell* [2013] for more details.
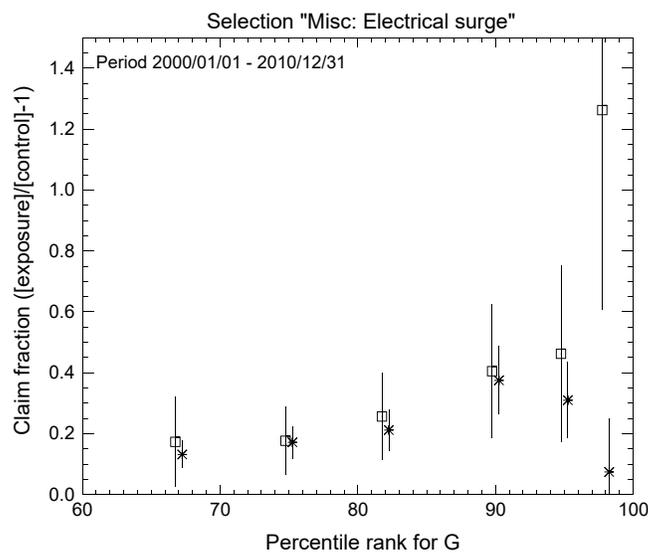
Figure 8. Same as Figure 7 but for sample *B* limited to those claims attributed to "Misc.: Electrical surge" (asterisks) (for 57% of the cases in that sample), compared to the fraction of high-voltage power grid disturbances statistically associated with geomagnetic activity (squares).

3. Testing for the Impact of Space Weather

In order to quantify effects of geomagnetic variability on the frequency of insurance claims filed for electrical and electronic equipment, we need to carefully control for a multitude of variables that include trends in solar activity, the structure and operation of the power grid (including, for example, scheduled maintenance and inspection), various societal and technological factors changing over the years, as well as the costs and procedures related to the insurance industry, and, of course, weather and seasonal trends related to the insolation angle and the varying tilt of the Earth's magnetic field relative to the incoming solar wind throughout the year.

There are many parameters that may influence the ionospheric current systems, the quality and continuity of electrical power, and the malfunctioning of equipment running on electrical power. We may not presume that we could identify and obtain all such parameters or that all power grid segments and all equipment would respond similarly to changes in these parameters. We therefore do not attempt a multiparameter correlation study but instead apply a retrospective cohort exposure study with tightly matched controls very similar to that applied by *Schrijver and Mitchell* [2013].

This type of exposure study is based on pairing dates of exposure, i.e., of elevated geomagnetic activity, with control dates of low geomagnetic activity shortly before or after each of the dates of exposure, selected from within a fairly narrow window in time during which we expect no substantial systematic variation in ionospheric conditions, weather, the operations of the grid, or the equipment powered by the grid. Our results are based on a comparison of claim counts on exposure dates relative to claim counts on matching sets of nearby control dates. This minimizes the impacts of trends (including "confounders") in any of the potential factors that affect the claim statistics or geomagnetic variability, including the daily variations in quiet-Sun irradiance and the seasonal variations as Earth orbits the Sun, the solar cycle, and the structure and operation of the electrical power network. This is a standard method as used in, e.g., epidemiology. We refer to *Wacholder et al.* [1992, and references therein] for a discussion on this method particularly regarding ensuring of time comparability of the "exposed" and control samples, to *Schulz and Grimes* [2002] for a discussion on the comparison of cohort studies as applied here versus case-control studies, and to *Grimes and Schulz* [2005] for a discussion of selection biases in samples and their controls (specifically their example on pp. 1429–1430).

We define a series of values of geomagnetic variability in order to form sets of dates including different ranges of exposure, i.e., of

Table 1. Probability (*p*) Values Based on a Kolmogorov-Smirnov Test That the Observed Sets of Claim Numbers on Geomagnetically Active Dates and on Control Dates Are Drawn From the Same Parent Distribution, for Date Sets With the Geomagnetic Activity Metric *G* Exceeding the Percentile Threshold in the Distribution of Values

	All Claims		Attributed to Electrical Surges	
Percentile	Set *A*	Set *B*	Set *A*	Set *B*
67	2×10^{-10}	2×10^{-19}	1×10^{-27}	0
75	3×10^{-7}	4×10^{-14}	8×10^{-20}	4×10^{-35}
82	0.0004	2×10^{-7}	1×10^{-13}	6×10^{-24}
90	0.010	0.0002	1×10^{-7}	8×10^{-13}
95	0.05	0.013	0.0001	2×10^{-7}
98	0.33	0.06	0.003	0.0001
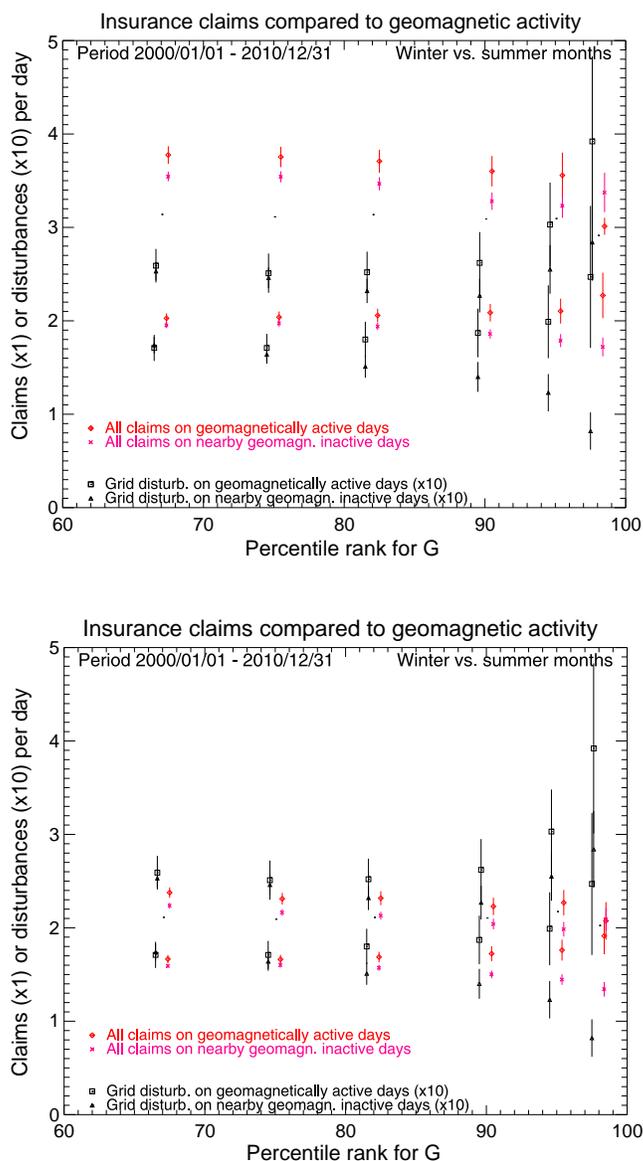
Figure 9. As Figure 5 but separating the winter half year (October through March) from the summer half year (April through September),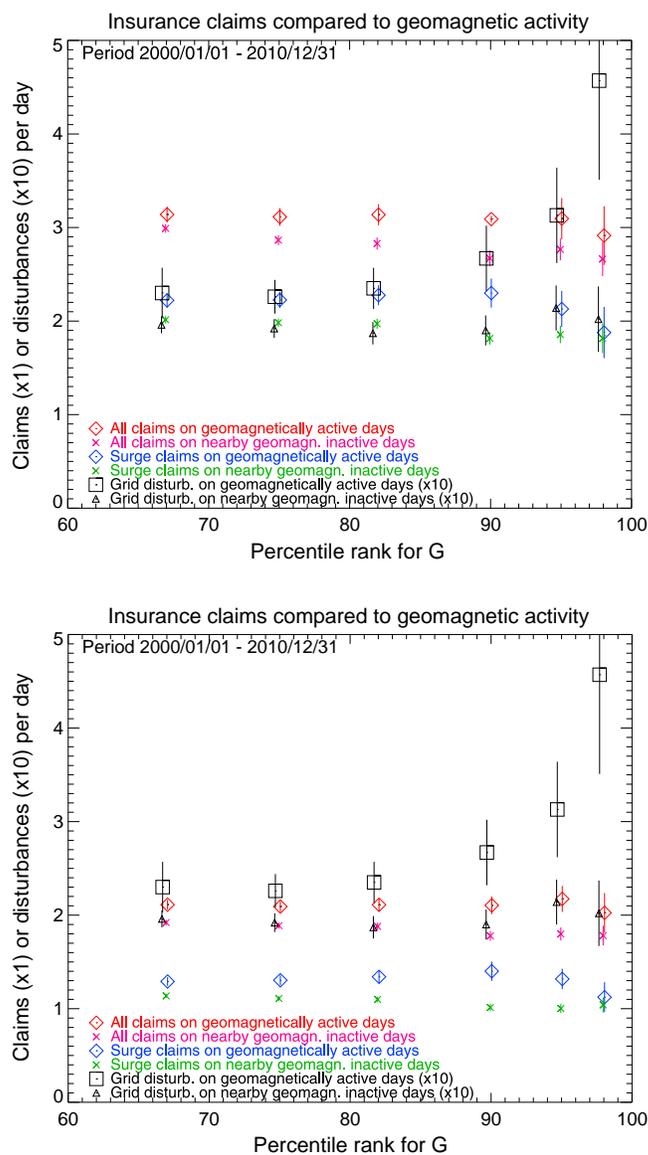 for (top) the full sample of insurance claims (set *A*) and (bottom) the sample from which claims likely unrelated to any space weather influence have been removed (set *B*). Values for the summer months are shown offset slightly toward the left of the percentiles tested (98, 95, 90, 82, 75, and 67), while values for the winter months are offset to the right. Values for the winter season are systematically higher than those for summer months.

geomagnetic variability, so that each high-exposure date is matched by representative low-exposure dates as controls. We create exposure sets by selecting a series of threshold levels corresponding to percentages of all dates with the most intense geomagnetic activity as measured by the metric *G*. Specifically, we determined the values of *G* for which geomagnetic activity, sorted from least active upward, includes 67%, 75%, 82%, 90%, 95%, and 98% of all dates in our study period. For each threshold value we selected the dates with *G* exceeding that threshold (with possible further selection criteria as described below). For each percentile set, we compute the mean daily rate of incident claims, n_i, as well as the standard deviation on the mean, σ_i, as determined from the events in the day-by-day claims list.

In order to form tightly matched control samples for low "exposure," we then select three dates within a 27 day period centered on each of the selected high-activity days. The 27 day period, also known as the Bartels period, is that characteristic of a full rotation of the solar large-scale field as viewed from the orbiting Earth; *G* values within that period sample geomagnetic variability as induced during one full solar rotation. This window for control sample selection is tighter than that used by *Schrijver and Mitchell* [2013] who used 100 day windows centered on dates with reported grid disturbances. For the present study we selected a narrower window to put even stronger limits on the potential effects of any possible long-term trends in factors that might influence claim statistics or geomagnetic variability. We note that there is no substantive change in our main conclusions for control windows at least up to 100 days in duration.

The three dates selected from within this 27 day interval are those with the lowest value of *G* smoothed with a 3 day running mean. We determine the mean claim rate, n_c, for this control set and the associated standard deviation in the mean, σ_c.

Figure 5 shows the resulting daily frequency of claims and the standard deviations in the mean, $n_i \pm \sigma_i$, for the selected percentiles, both for the full sample *A* (top) and for sample *B* (bottom) from which claims were omitted that were attributed to causes not likely associated directly or indirectly with geomagnetic

Figure 10. As Figure 9 but separating the months around the equinoxes (February–April and August–October) from the complementing months around the solstices, for the full sample of insurance claims (set *A*). Values for the equinox periods are shown offset slightly toward the left of the percentiles tested (98, 95, 90, 82, 75, and 67), while values for the solstice months are offset to the right. Mean claim frequencies for the solstice periods are systematically higher than those for equinox periods, but the frequencies for high-*G* days in excess of the control sample frequencies are slightly larger around the equinoxes than around the solstices.

activity. For all percentile sets, we see that the claim frequencies n_i on geomagnetically active days exceed the frequencies n_c for the control dates.

The frequency distributions of insurance claims are not Poisson distributions, as can be seen in the example in Figure 6 (left): compared to a Poisson distribution of the same mean, the claims distributions on geomagnetically active dates, $N_{B,a,75}$, and for control days, $N_{B,c,75}$, are skewed to have a peak frequency at lower numbers and a raised tail at higher numbers; a Kolmogorov-Smirnov (KS) test suggests that the probability that $N_{B,c,75}$ is consistent with a Poisson distribution with the same mean is 0.01 for this example. The elevated tail of the distribution relative to a Poisson distribution suggests some correlation between claim events, which is of interest from an actuarial perspective as it suggests a nonlinear response of the power system to space weather that we cannot investigate further here owing to the signal-to-noise ratio of the results given our sample.

For the case shown in Figure 6 for the 25% most geomagnetically active dates in set *B*, a KS test shows that the probability that $N_{B,a,75}$ and $N_{B,c,75}$ are drawn from the same parent distribution is of order 10^{-14}, i.e., extremely unlikely.

The numbers that we are ultimately interested in are the excess frequencies of claims on geomagnetically active dates over those on the control dates and their uncertainty. For the above data set, we find and excess daily claims rate of $(n_{B,i} - n_{B,c}) \pm \sigma_B = 0.20 \pm 0.08$. The uncertainty σ_B is in this case determined by repeated random sampling of the claim sample for exposure and control dates and subsequently determining the standard deviation in a large sample of resulting excess frequencies (using the so-called bootstrap method). The distribution of excess frequencies (shown in Figure 6 (right)) is essentially Gaussian, so that the metric of the standard deviation gives a useful value to specify the uncertainty. We note that the value of σ_B is comparable to the value $\sigma_{a,c} = (\sigma_a^2 + \sigma_b^2)^{1/2}$ derived by combining the standard deviations for the numbers of claims per day for geomagnetically active dates and the control dates, which in this case equals $\sigma_{a,c} = 0.07$. Thus, despite the skewness of the claim count distributions relative to a Poisson distribution as shown in the example in Figure 6 (left), the effect of that on the uncertainty in the excess claim rate is relatively small. For this reason, we show the standard deviations on the mean frequencies in Figures 5–11 as a useful visual indicator of the significance of the differences in mean frequencies.

Figure 7 shows the relative excess claim frequencies, i.e., the relative differences $r_e = (n_i - n_c)/n_c$ between the claim frequencies on geomagnetically active dates and those on the control dates, thus quantifying the claim fraction statistically associated with elevated geomagnetic activity. The uncertainties shown are computed as $\sigma_e = (\sigma_i^2/n_i^2 + \sigma_c^2/n_c^2)^{1/2} r_e$, i.e., using the approximation of normally distributed uncertainties, warranted by the arguments above. We note that the relative rate of claims statistically associated with space weather is slightly higher for sample *B* than for the full set *A* consistent with the hypothesis that the claims omitted from sample *A* to form sample *B* were indeed preferentially unaffected by geomagnetic activity. Most importantly, we note that the rate of claims statistically associated with geomagnetic activity increases with the magnitude of that activity.

Claim fractions attributable to SW compared to geomagnetic activity

Claim fractions attributable to SW compared to geomagnetic activity
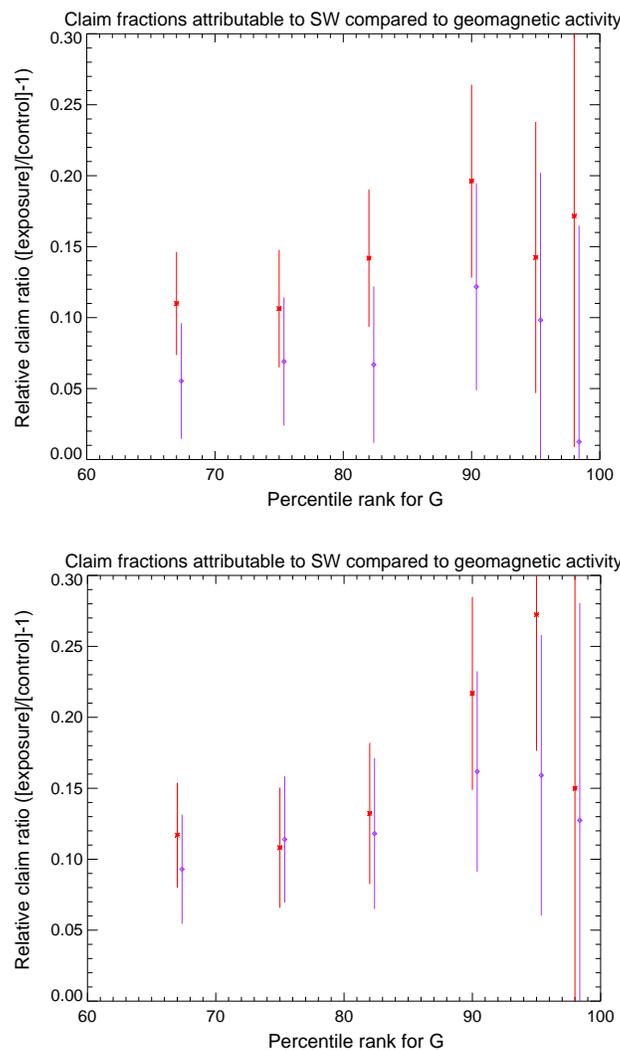
Figure 11. Relative excess claim frequencies ($(n_i - n_c)/n_i$) on geomagnetically active dates relative to those on control dates for geomagnetic latitudes below 49.5°N (asterisks, red) compared to those for higher latitudes (diamonds, purple; offset slightly to the right) for the percentiles tested (98, 95, 90, 82, 75, and 67). (top) The results for the full sample (A) and (bottom) for sample B from which apparently nonspace weather-related events were removed (see section 2.1).

About 59% of the claims in sample B attribute the case of the problem to "Misc.: Electrical surge", so that we can be certain that some variation in the quality or continuity of electrical power was involved. Figure 8 shows the relative excess claim rate $(n_i - n_c)/n_c$ as function of threshold for geomagnetic activity. We compare these results with the same metric, based on identical selection procedures, for the frequency of disturbances in the high-voltage power grid (squares). We note that these two metrics, one for interference with commercial electrical/electronic equipment and one for high-voltage power, agree within the uncertainties, with the possible exception of the infrequent highest geomagnetic activity (98 percentile) although there the statistical uncertainties on the mean frequencies are so large that the difference is less than 2 standard deviations in the mean values.

To quantify the significance of the excess claim frequencies on geomagnetically active days, we perform a nonparametric Kolmogorov-Smirnov (KS) test of the null hypothesis that the claim events on active and on control days could be drawn from the same parent sample. The resulting p values from the KS test, summarized in Table 1, show that it is extremely unlikely that our conclusion that geomagnetic activity has an impact on insurance claims could be based on chance, except for the highest percentiles in which the small sample sizes result in larger uncertainties. We note that the p values tend to decrease when we eliminate claims most likely unaffected by space weather (contrasting set A with B) and when we limit either set to events attributed to electrical surges: biasing the sample tested toward issues more likely associated with power grid variability increases the significance of our findings that there is an impact of space weather.

Figure 9 shows insurance claims differentiated by season: the frequencies of both insurance claims and power grid disturbances are higher in the winter months than in the summer months, but the excess claim frequencies statistically associated with geomagnetic activity follow similar trends as for the full date range. The same is true when looking at the subset of events attributed to surges in the low-voltage power distribution grid.

Figure 10 shows a similar diagram to that of Figure 9 (top), now differentiating between the equinox periods and the solstice periods. Note that although the claim frequencies for the solstice periods are higher than those for the equinox periods, that difference is mainly a consequence of background (control) frequencies:

the fractional excess frequencies on geomagnetically active days relative to the control dates are larger around the equinoxes than around the solstices.

Figure 11 shows the comparison of claim ratios of geomagnetically active dates relative to control dates for states with high versus low geomagnetic latitude, revealing no significant contrast (based on uncertainties computed as described above for Figure 7).

4. Discussion and Conclusions

We perform a statistical study of North American insurance claims for malfunctions of electronic and electrical equipment and for business interruptions related to such malfunctions. We find that there is a significant increase in claim frequencies in association with elevated variability in the geomagnetic field, comparable in magnitude to the increase in occurrence frequencies of space weather-related disturbances in the high-voltage power grid. In summary,

1. The fraction of insurance claims statistically associated with geomagnetic variability tends to increase with increasing activity from about 5 to 10% of claims for the top third of most active days to approximately 20% for the most active few percent of days.
2. The overall fraction of all insurance claims statistically associated with the effects of geomagnetic activity is $\approx$ 4%. With a market share of about 8% for Zurich NA in this area, we estimate that some 500 claims per year are involved overall in North America.
3. Disturbances in the high-voltage power grid statistically associated with geomagnetic activity show a comparable frequency dependence on geomagnetic activity as do insurance claims.
4. We find no significant dependence of the claim frequencies statistically associated with geomagnetic activity on geomagnetic latitude.

For our study, we use a quantity that measures the rate of change of the geomagnetic field regardless of what drives that. Having established an impact of space weather on users of the electric power grid, a next step would be to see if it can be established what the relative importance of various drivers is (including variability in the ring current, electrojet, substorm dynamics and solar insolation of the rotating Earth), but that requires information on the times and locations of the impacts that is not available to us.

The claim data available to us do not allow a direct estimate of the financial impacts on industry of the malfunctioning equipment and the business interruptions attributable to such malfunctions: we do not have access to the specific policy conditions from which each individual claim originated, so we have no information on deductable amounts, whether (contingency) business interruptions were claimed or covered or were excluded from the policy, whether current value or replacement costs were covered, etc. Moreover, the full impact on society goes well beyond insured assets and business interruptions, of course, as business interruptions percolate through the complex of economic networks well outside of direct effects on the party submitting a claim. A sound assessment of the economic impact of space weather through the electrical power systems is a major challenge, but we can make a rough order-of-magnitude estimate based on existing other studies as follows.

The majority (59% in sample *B*) of the insurance claims studied here are explicitly attributed to "Misc.: electrical surge," which are predominantly associated with quality or continuity of electrical power in the low-voltage distribution networks to which the electrical and electronic components are coupled. Many of the other stated causes (see section 2.1) may well be related to that, too, but we cannot be certain given the brevity of the attributions and the way in which these particular data are collected and recorded. Knowing that in most cases the damage on which the insurance claims are based is attributable to perturbations in the low-voltage distribution systems, however, suggests that we can look to a study that attempted to quantify the economic impact of such perturbations on society.

That study, performed for the Consortium for Electric Infrastructure to Support a Digital Society [*Lineweber and McNulty*, 2001], focused on the three sectors in the U.S. economy that are particularly influenced by electric power disturbances: the digital economy (including telecommunications), the continuous process manufacturing (including metals, chemicals, and paper), and the fabrication and essential services sector (which includes transportation and water and gas utilities). These three sectors contribute approximately 40% of the U.S. gross domestic product.

Lineweber and McNulty [2001] obtained information from a sampling of 985 out of a total of about 2 million businesses in these three sectors. The surveys assessed impact by "direct costing" by combining statistics on grid disturbances and estimates of costs of outage scenarios via questionnaires completed by business officials. Information was gathered on grid disturbances of any type or duration, thus resulting in a rather complete assessment of the economic impact. The resulting numbers were corrected for any later actions to make up for lost productivity (actions with their own types of benefits or costs).

For a typical year (excluding, for example, years with scheduled rolling blackouts due to chronic shortages in electric power supply), the total annual loss to outages in the sectors studied is estimated to be $46 billion and to power-quality phenomena almost $7 billion. Extrapolating from there to the impact on all businesses in the U.S. from all electric power disturbances results in impacts ranging from $119 billion/yr to $188 billion/yr (for about year 2000 economic conditions).

Combining the findings of that impact quantification of all problems associated with electrical power with our present study on insurance claims suggests that, for an average year, the economic impact of power-quality variations related to elevated geomagnetic activity may be a few percent of the total impact or several billion dollars annually. That very rough estimate obviously needs a rigorous follow up assessment, but its magnitude suggests that such a detailed, multidisciplinary study is well worth doing.

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Exhibit I

"Estimating the Cost of Protecting the U.S. Electric Grid from Electromagnetic Pulse." Foundation for Resilient Societies. September 2020.

Estimating the Cost of Protecting the U.S. Electric Grid from Electromagnetic Pulse

Foundation for Resilient Societies

Estimating the Cost of Protecting the U.S. Electric Grid from Electromagnetic Pulse

Foundation for Resilient Societies

Last Revised: September 2020

Cover Image: Adapted from City Lights of the Americas. NASA Earth Observatory image by Robert Simmon, using Suomi NPP VIIRS data provided courtesy of Chris Elvidge (NASA/NOAA).

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List of Acronyms

AC   Alternating Current

CCTV   Closed Circuit Television

DC   Direct Current

DoD   Department of Defense

DOE   Department of Energy

EHV   Extra High-voltage

EMP   Electromagnetic Pulse

FERC   Federal Energy Regulatory Commission

GIC   Geomagnetically Induced Current

GMD   Geomagnetic Disturbance

GSU   Generator Step-up (transformer)

HEMP   High-altitude Electromagnetic Pulse

HILF   High Impact Low Frequency

HV   High Voltage

HVDC   High-voltage Direct Current

kV   Kilovolt

MOV   Metal Oxide Varistor

MW   Megawatts

PLC   Programmable Logic Controller

RTU   Remote Terminal Unit

SCADA Supervisory Control and Data Acquisition

SVC   Static Var Compensators

SEL   Schweitzer Engineering Laboratories
SQL   Sequential Query Language

UPS   Uninterruptible Power Supply

VOLL   Value of Lost Load

Executive Summary

The prospective cost and benefits of protecting the U.S. electric grid from electromagnetic pulse (EMP) have been largely missing from public discourse, despite many government reports and Congressional testimonies conveying the risk America faces from both high-altitude electromagnetic pulse (HEMP) attack and geomagnetic disturbance (GMD).[*] This report provides for public policy consideration a transparent, bottom-up cost estimate of HEMP and GMD protection. Our estimates are approximate, absent previous experience in protecting electric grids from EMP on a continent-wide scale, and should be refined by further engineering and economic study.

To estimate the cost of EMP protection, we developed a database of key electric grid facilities, including generation plants, substations, and control rooms. The database allowed us to estimate counts for each facility type and components within facilities. We then estimated EMP protection costs for each facility and component based on these drivers:
- For generation plants: megawatt capacity, technology, and grid connection voltage
- For substations: high-side transformer voltage and number of circuits when available
- For control rooms: entity type (generation dispatch, transmission operator, reliability coordinator, etc.) and generation capacity or peak load controlled

Our data sources for per-facility and per-component protection costs include:
- For generation plants: construction costs for plant electrical and electronic equipment published by the U.S. Energy Information Administration (EIA)
- For substations: equipment cost surveys and interviews with industry vendors
- For control rooms: Congressional testimony and cost experience of large utilities.

To produce our EMP protection cost estimates, we relied on simple mathematical calculations. First, we multiplied the counts of facilities and components by per-unit protection costs. We then aggregated the per-facility cost estimates by state, protection type, and facility category, and then for the United States as a whole. We calculated per-capita protection costs by dividing protection costs by population statistics obtained from the U.S. Census Bureau. We calculated potential increases in electricity billings by comparing protection costs to billing data obtained from the U.S Energy Information Agency (EIA).

Key findings are:
- Our estimated cost to protect the bulk power system portion of the U.S. electric grid from HEMP pulses caused by nuclear detonations and also from GMD caused by solar storms is on the order of $25.5 billion annually, comparable to other important societal expenditures.
- The vast majority of this cost—98%—would be for E1 protection against HEMP E1 while only 2% of the costs would be for HEMP E3 protection and concurrent GMD protection.
- Among grid facilities, generation plants would be the costliest to protect, accounting for 70% of estimated costs, followed by substations accounting for an estimated 29% of costs. Control rooms would be a minor portion of the total, accounting for 1% of costs.
- On a per capita basis, EMP protection could cost $79 per year.
- As a percent of electricity billings, EMP protection could add 7% to average electricity rates.
- EMP protection could avoid trillions in lost GDP and save millions of American lives.

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[*] Throughout this report, the term "electromagnetic pulse" or "EMP" refers to both HEMP and GMD.

1. Introduction

The U.S. electric grid is the keystone infrastructure upon which all other critical infrastructures depend. Unfortunately, the U.S. electric grid is vulnerable to EMP from manmade sources as an act of war and naturally occurring GMD from solar phenomena.

Both manmade and natural EMP can damage key grid components and generate wide-area blackouts, leaving portions of the grid unrestorable for an extended period.[1] This study postulates a level of EMP protection that would enable prompt restoration of the electric grid following a HEMP or extreme GMD event. Qualitatively, the goal for our assumed level of protection is that HEMP or GMD should not cause widespread, long-lasting outages.

Figure 1: United States at Night. Composite image showing the extent of the U.S. electric grid—the world's largest integrated machine—by the expanse of electric lights. Few societal undertakings would match the scope and importance of protecting America's electric grid from the existential threat of EMP. Photo credit: NASA/NOAA

Serious policy debate on hardening the grid requires an assessment of both the grid's vulnerabilities and costs of protection. While the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack published several assessments of electric grid vulnerability, no rigorous and publicly available assessment of the costs of EMP protection has been produced. This report makes two significant contributions towards that end:

1) We establish a transparent methodology for estimating costs of EMP protection—determining the categories and numbers of grid facilities and components to be protected and multiplying by the per-facility or per-component cost. This framework can be iterated as understanding of vulnerabilities, protections, and protection costs improves.
2) We propose initial cost estimates for hardening the U.S. electric grid from electromagnetic threats; policymakers can use these estimates to budget for more detailed cost studies or to implement actual EMP protections.

Electromagnetic Pulse Threats

Electromagnetic pulse threats arise from intense pulses of electromagnetic radiation over a wide range of frequencies. This report is concerned with two threats that can produce wide-area effects: HEMP and GMD.

High-Altitude Electromagnetic Pulse

HEMP results from the detonation of a nuclear weapon at high-altitude (between 40 and 400 kilometers above the surface of the earth). HEMP is composed of several distinct pulses termed E1, E2, and E3. Gamma radiation from the nuclear detonation ionizes the atmosphere. Interaction of electrons released from ionization with the earth's magnetic field creates the fast acting E1 pulse. Gamma radiation, released from delayed reactions that follow the initial burst, creates the E2 pulse via a similar mechanism.[2] Finally, the explosion's deflection of the Earth's magnetic field generates the slower acting E3 pulse, also termed the magnetohydrodynamic (MHD) pulse.[3]
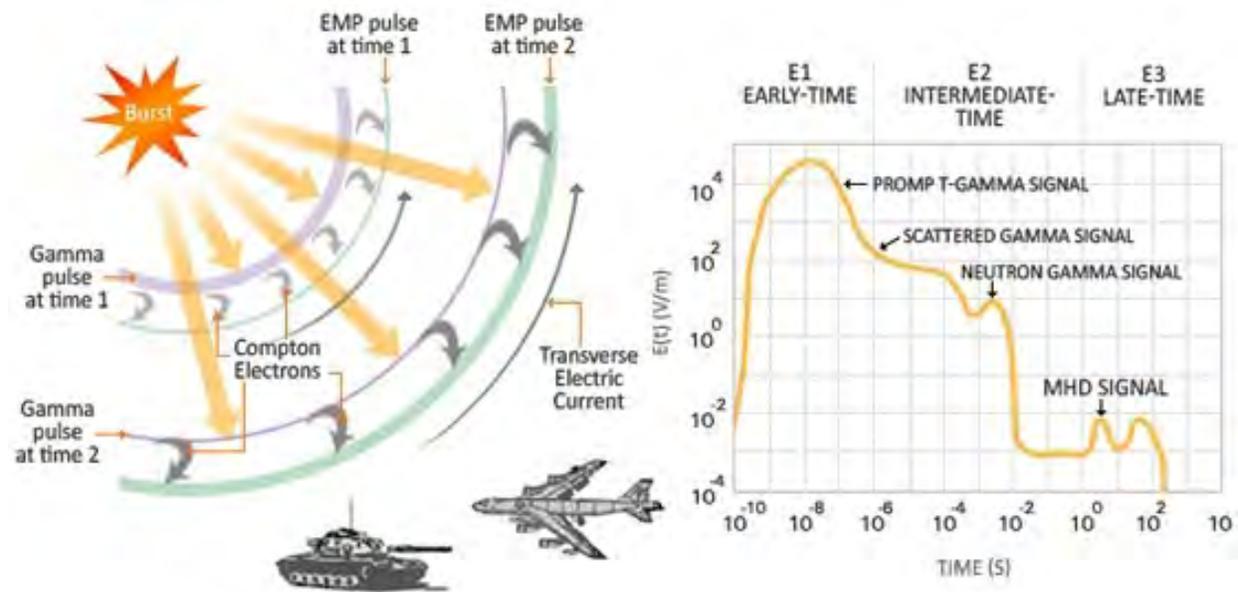
Figure 2: Production of High-altitude Electromagnetic Pulse. A nuclear weapon detonating in the upper atmosphere produces a series of electromagnetic pulses starting at approximately one pico-second after the burst and extending for several minutes. These pulses can cause failures in equipment with electrical systems, both aloft and on the ground. Photo credit: Defense Threat Reduction Agency

The E1 pulse has the greatest peak power and is particularly damaging to the microprocessors common in digital electronics, which are designed to operate at low power. The effect of the E2 pulse is similar to lightning. Much of the U.S. electric grid is already hardened against lightning; therefore, this report addresses the E2 pulse in lesser detail. The E3 pulse has a lower peak power but a longer duration, leading to a larger amount of energy deposition. The slower E3 pulse couples to very long conductors, such as overhead transmission lines, and induces a quasi-DC power flow that can damage systems designed to operate under AC conditions. [3] [4]

Atmospheric nuclear tests conducted during the Cold War era provided data on HEMP effects. In 1962, the United States conducted Operation Fishbowl, a series of high-altitude nuclear tests over the Pacific Ocean. Starfish Prime, one of the tests conducted during that operation, produced effects on the Hawaiian grid 800 miles from ground zero. The HEMP reportedly blew fuses for thirty strings of electrical street lights and tripped numerous substation circuit breakers.[2] This same year, the Soviet Union conducted its own high-altitude tests over Kazakhstan, which resulted in electrical fires and direct damage to diesel generators, electrical substations, and communication lines.[5] Since these Cold War-era tests, the grid has evolved and widely employs digital controls, which are more susceptible to malfunction and damage under E1 HEMP conditions.[6]

Geomagnetic Disturbance

Geomagnetic disturbance is caused by solar storms that deflect the Earth's magnetic field. Charged particles in coronal mass ejections warp the magnetic field, inducing electric currents in conductors on the Earth's surface. The effect of GMD is similar to the effect of the E3 component of HEMP, but typically generates a weaker electric field that persists for a longer time.[7]
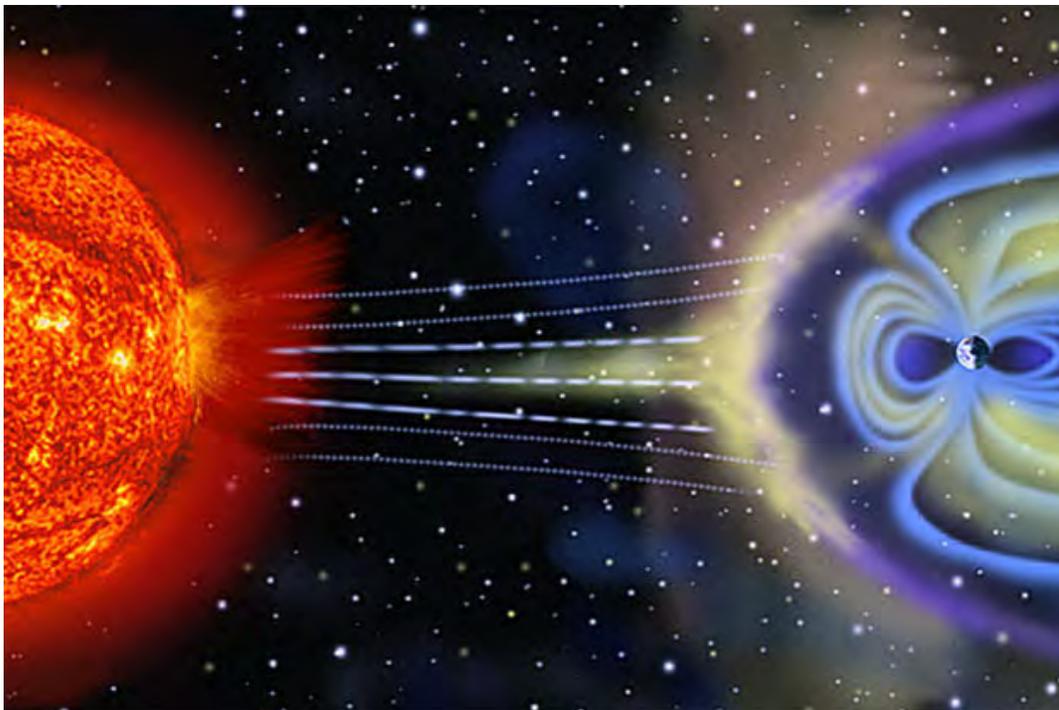
Figure 3: Coronal Mass Ejection from the Sun Causing a Geomagnetic Disturbance on Earth. Charged particles emitted from sun impinge on earth's magnetic field, causing its disturbance. As the magnetic field shifts, current is induced in long conductors on the earth's surface. Graphic credit: NASA.

The Carrington Event of 1859 provided initial experience with the effects of GMD on long conductors in telegraph lines. This intense solar storm created a visible aura borealis as far south as the Caribbean. The GMD produced by the storm created arcs in equipment, disrupted communications, and at times even permitted telegraph operation without connection to a power source. [7] [8]

The solar storm of March 1989 was less intense than the Carrington Event, but precipitated a cascading collapse of the Quebec power system and damage to extra high-voltage (EHV) transformers in the United States. Failure of the Quebec system was initiated by relays sensing effects of the GMD and tripping seven static VAR compensators (SVCs) in Canada as a protective measure. The loss of multiple SVCs over a short period created a loss of reactive power and a substantial voltage drop, ultimately leading to system collapse.[9] A generator-step up (GSU) transformer at the Salem Nuclear Power Plant was severely damaged during the storm due to overheating. Several other large GSUs failed soon after the storm, possibly because of degradation caused by the event.[7]

Current Status of EMP Threats

A long-term, wide-area power outage is an existential threat to the United States. Power grids are complex networks susceptible to cascading collapse; failure of a small percentage of components can cause partial or even complete collapse of the network. The conclusions of a power-flow study produced by the Federal Energy Regulation Commission (FERC) provide a poignant example: loss of various combinations of only nine key substations—out of a network of 55,000—could blackout the entire U.S. grid for weeks or months.[10] Both HEMP and GMD pose risks of concurrent component failures across this wide, complex network.

Geomagnetic disturbance represents a chronic risk to the U.S. electric grid. Although GMD events have caused geographically widespread outages without long-term blackouts, no modern electric grid has ever been subjected to an event as intense as the 1859 Carrington storm. A Carrington-class event could be an order of magnitude more intense than the March 1989 storm.[11] One published estimate of the probability of a Carrington class event is 10% per decade.[12]

A high-altitude EMP event over or near U.S. territory would constitute an attack on the United States. EMP is known to be part of the military strategy of other nuclear powers and nuclear aspirants. For example, official North Korean outlets have explicitly defined the ability to execute an EMP strike against the United States as a "strategic goal" of the regime's nuclear program.[13]

Increasing EMP Vulnerabilities

After the end of the Cold War, national security policymakers shifted their focus from nuclear weapon threats, including EMP, to "peace dividends." Simultaneously, vulnerabilities to EMP have increased dramatically throughout civilian critical infrastructures. These inadvertent vulnerabilities have been largely the byproduct of other trends, including reliance on high-speed, compact digital circuity; use of cheap, ubiquitous telecommunications (including the Internet); and long-distance transmission of electricity.

To this day, standard engineering practice for nearly all civilian infrastructures, including engineering of electric grid components, fails to consider EMP protection in equipment design and operation. The result, as the reader will see through numerous examples in this report, is pervasive vulnerability to EMP.

Use of digital controls and E1-exposed (but easily accessed and maintained) sensors, communications cabling, and power cords is preferred practice—accounting for much of the EMP problem. Long-distance electricity transmission results in power that is cheaper and cleaner but unreliable during solar storms.

The expense of EMP protection could have been greatly reduced had standards for such protection been incorporated into designs of electric grid equipment soon after the 1962 Starfish Prime test. EMP protection costs—including the cost of retrofits—will continue to escalate if equipment is not designed and manufactured for EMP resilience.

2. EMP Protection Techniques

E1 Protection

The E1 pulse induces electric fields in the 50 kV/meter regime.[†] Electrical conductors, such as cables, collect the electromagnetic energy and direct it into vulnerable components. A long cable is not requisite to produce a high-induced voltage from E1. For example, a 50 kV/meter pulse of optimum polarization exposing a 1-meter cable can induce a 50 kV potential between the ends.

While the total energy carried by the E1 pulse is low, the pulse is extremely brief and causes large power spikes, impinging on electronics that rely on sensitive, integrated circuits. The E1 pulse can destabilize semiconductor junctions, causing them to self-destruct under powered-on conditions. Moreover, the E1 pulse can cause power supplies to malfunction, feeding harmful voltages to equipment.

Devices can be shielded from E1 fields by enclosure in a three-dimensional conductive shield known as a Faraday cage. For good EMP protection, any apertures must be small relative to the wavelength of electromagnetic radiation impinging on the cage.

While Faraday cages are effective shields, the infeasibility of enclosing large systems should be readily apparent—most generation plants and substations are too big for this solution. Enclosing individual devices is more feasible but can also be problematic. Conductive cables penetrating the Faraday cage will act as funnels for the electromagnetic energy, collecting and directing it into equipment within. This issue can be mitigated by using non-conductive fiber optic cables, using shielded cables, or incorporating protective devices at points of entry into the cage (e.g., ferrite cores).

It is important to note that the E1 pulse travels at a speed that makes operational procedures ineffective for protection following a HEMP event. When a nuclear weapon detonates, the E1-induced current pulse reaches its highest amplitude in less than 10-50 nanoseconds, a small fraction of the time duration of a single cycle in a 60 Hz system. No procedural protection can be implemented in such a timeframe.

E3 and GMD protection

The E3 pulse and GMD induce lower amplitude fields than the E1 pulse but at a longer wavelength. Threat E3 waveforms extrapolated from the Soviet nuclear EMP test measurements peak at 85 V/km.[14] Threat levels for GMD can be up to 30 volts/kilometer. These pulses can act over larger areas and longer times, depositing more energy on the illuminated system. To pick up appreciable effects from long wavelength

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[†] Nuclear weapons designed specifically for EMP generation may produce higher E1 levels.

E3 and GMD, conductors typically must be miles long, such as conductors found in long-distance transmission lines.

Electric transmission lines form a conductive loop consisting of the overhead conductors, transformer windings, and conductive ground path. An electric current is induced as the E3 or GMD shifts the Earth's magnetic field through this loop. Geomagnetically induced currents (GICs) can be approximated as quasi-direct current (DC).

Geomagnetically induced current with its DC characteristics causes malfunction of grid components designed to operate in an AC environment. Issues include component overheating, induced harmonics, and malfunction of sensors designed to monitor AC signals.

Capacitors are an effective means of protecting transmission systems against E3 and GMD. Capacitors may be placed in series with transmission lines, blocking the DC current while allowing AC to pass. Alternatively, DC current passing through the neutrals of generator and substation transformers may be blocked with capacitors. Because the E3 pulse reaches its peak value seconds later than the E1 pulse, E3 protective devices could be effectively triggered by E1 using automated procedures. For GMD, there is sufficient time to switch in capacitors when the early stages of solar storms are detected by monitoring DC currents.

3. Methodology

We apply a bottom-up methodology to estimate the cost of protecting generation and transmission facilities and their control systems. Broadly, the approach is to multiply the unit costs of EMP protection by the number of facilities or components and sum the results. Where unit costs for protection are not available, replacement costs are used instead.

Section 5 of this report summarizes the expected vulnerabilities of each facility or component based on literature reviews and interviews with experts. Section 6 proposes protection mechanisms for the vulnerabilities summarized in the preceding section and estimates cost of implementation. Section 7 examines testing for EMP protection. Section 8 counts and characterizes the facilities or components. Section 9 calculates our initial estimates of HEMP and GMD protection and examines cost factors and policy implications. Section 10 discusses the societal benefits for protecting against HEMP and GMD. Section 11 presents key conclusions from the report. Section 12 briefly summarizes opportunities for future work.

The EMP protection costs estimated in this report are intended to be the first in an iterative process. The Foundation for Resilient Societies invites comments and suggestions to improve vulnerability assessments, EMP protection strategies, counts of facilities and their components, and per-unit protection costs. Ultimately, no major electric grid has been comprehensively protected against EMP; therefore, any cost estimates for protection are necessarily approximate.

Grid Assets Covered

To assure electric grid restoration, multiple classes of assets would require prioritized EMP protections, including electric generation plants, transmission systems, control rooms, and the communication systems that coordinate these systems. We assume protection of electric grid assets operating at a voltage of 100kV or above, which is defined under federal regulatory standards as the "bulk power system." To gain size efficiencies for protecting generation stations, we assume protection only for dispatchable

generators with at least 100MW capacity. Likewise, we assume protection for control rooms dispatching at least 100MW of total capacity. Hydro plants with at least 10MW capacity are also protected in our methodology, since they are cheaper to protect than other generation resources and are important for black start.
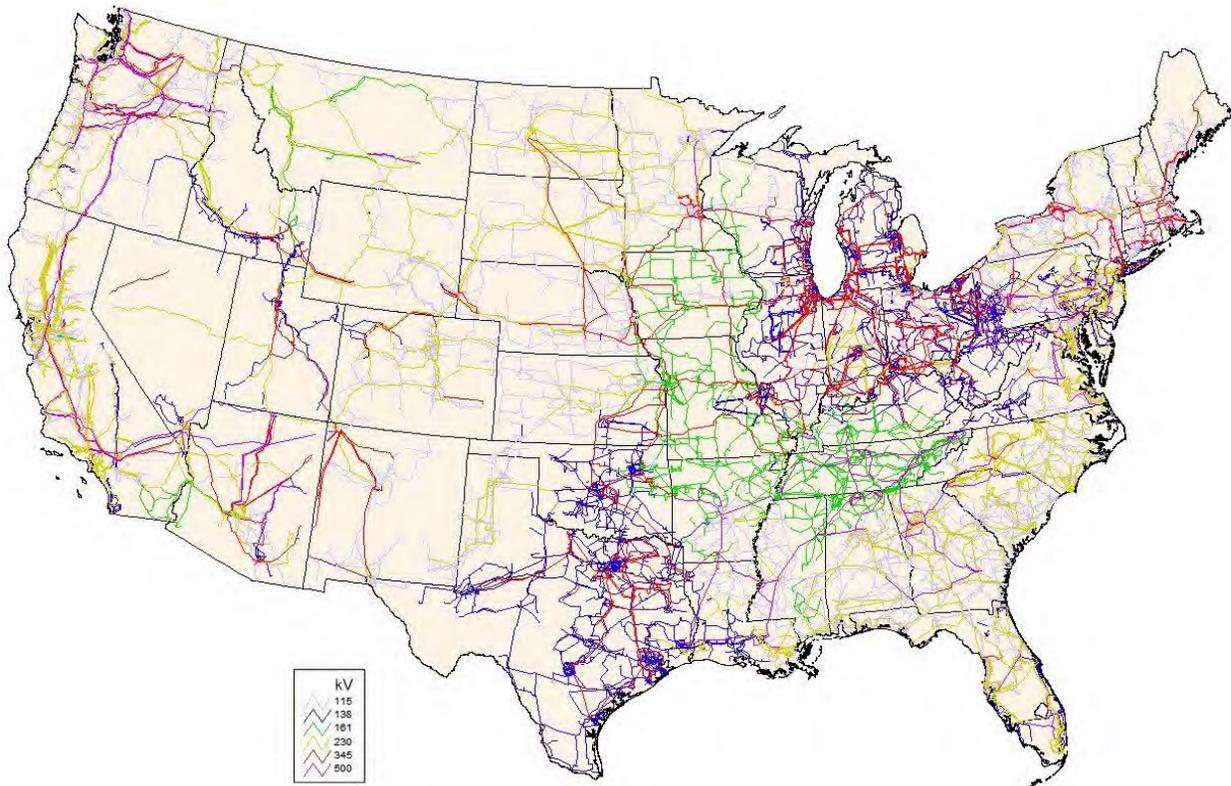
Figure 4: United States Bulk Power System. America's electric grid uses transmission lines in the bulk power system to transport energy from generation plants often located long distances from local consumers. Varying voltage levels are employed. Graphic credit: Federal Emergency Management Agency

This study does not address EMP protection for wind, solar thermal, solar photovoltaic generation technologies because they are non-dispatchable during grid restoration if weather conditions are not supportive. However, renewable energy will positively contribute to the energy balance of the grid and could delay depletion of fuel reserves after an EMP event. Protecting renewable technologies from EMP deserves future technical and economic study.

We do not examine the cost of protecting local distribution systems at voltages less than 100 kV, nor do we examine the vulnerability of customer loads to EMP. Partial failures in local distribution systems and on customer premises are less likely to cause wide-area, long-term electric grid collapse. Moreover, failure in local distribution systems should not prevent restoration of the bulk power system. Nonetheless, long-lasting outages of these systems could degrade societal functioning and cause loss of life.

Costing Approaches

This study applies two approaches in estimating the per-unit costs of EMP protection. The direct approach estimates unit costs directly, describing the strategy to be applied and estimating the material and installation costs of each protective device. When this approach cannot be used, we estimate protection costs indirectly from the replacement costs of protected assets.

Using the direct approach, we estimate unit costs for the transmission system and for control rooms. Material and installation costs may be tied to a cost driver that accounts for scaling (e.g., the cost of a higher voltage protective device or a larger Faraday cage). Where applicable, estimation of unit costs draws on U.S. Department of Defense (DoD) experience with EMP hardening. However, while the DoD has protected certain electronic systems against HEMP, its protection techniques and costs are not always applicable to the electric power systems and components.

We use the replacement cost approach for generation facilities. This cost estimation technique, while crudely approximate, is necessary due to the current lack of both engineering studies and experience in protecting generation plants against EMP. This method could result in an overestimation of costs when control systems can be easily enclosed in small EMP-shielded barriers. It could also result in an underestimation of costs when integrating EMP protection into non-electrical components of an overall system is difficult.

4. Electric Grid Vulnerability to EMP

A necessary first step in assessing the cost of comprehensive EMP protection for the U.S. electric grid is a determination of which grid components are susceptible to damage or upset by EMP environments and, therefore, require protection. Alternatively, certain grid components may be inherently resilient to EMP and, therefore, protection costs are likely negligible. For example, transmission system pylons are unlikely to be directly damaged by EMP. In contrast, equipment using unshielded integrated circuitry is likely to be highly vulnerable to EMP.

Because of a lack of controlled experiments on components within an operational electric grid, the degree of component vulnerability in many cases requires more study, including hardware testing. Testing will also be needed to confirm EMP protections. Since conducting controlled experiments on operating power systems is risky and often infeasible, other methods can be used to assess component vulnerability. This report draws on several methods; each is imperfect but has merit:

- Historical cases
- Physical experiments of components in isolation
- Mathematical models, analysis, and simulations
- Expert judgement

The historical cases:

- 1962 American and Soviet high-altitude nuclear weapons tests provide limited experience on the reaction of operational, interconnected electrical grids to the actual threat environment. Of importance for HEMP is the exposure of an operating electrical system to E1, E2, and E3 threats in succession.

- A moderate solar storm In March 1989 caused a cascading blackout for the province of Quebec, Canada.
- Smaller solar storms in 2003 caused tripping of the Phase II High-voltage Direct Current (HVDC) transmission line from Quebec to Ayer, Massachusetts.

The U.S. electric grid has evolved substantially since these prior EMP events. Digitization has increased vulnerability to HEMP E1.[6] More long-distance transmission lines have increased vulnerability to both the HEMP E3 pulse and GMD.

Physical EMP experiments are typically conducted on components in isolation or on small test systems. The threat environment is an artificially induced electromagnetic field or pulse current injection. These experiments allow replicability and a degree of control, but rely on accurate assumptions of the threat environment. EMP experiments cannot be safely conducted on an operational, interconnected grid and, in the case of HEMP, cannot replicate the rapid E1, E2, E3 sequence. Additionally, physical tests on expensive grid components have been limited; testing at high threat levels is likely to be destructive and increases the cost of testing. This complication is especially true for generators and high-voltage transformers that cost millions of dollars per unit.

Mathematical models and simulations should be based on empirical failure data from historical cases and physical tests conducted on a smaller scale. Some models may attempt to account for the interdependencies of an operational grid. Models, however, are only as good as the assumptions upon which they are built. Validating these assumptions is particularly difficult for the complex system-of-systems that is the electric grid. Without empirical test data on system failures, analytical uncertainties inherent in EMP effects models can be orders of magnitude.[15]

Expert judgement is the synthesis of a career of experience and analysis in grid operation and electromagnetic protection and its extrapolation to new situations. While able to produce flexible insights, the conclusions from expert judgement are not transparently derived.

The vulnerability assessments presented here are our best synthesis of the existing literature and interviews with subject matter experts. Significant uncertainties in component vulnerability to HEMP and GMD remain in many instances due to the lack of test data. Cost estimates for EMP protection should be updated when more test data is available.

Overview of Grid Components

The U. S. electric grid is a meshed network of generating stations with step up transformers, high-voltage transmission lines, substations with step-down transformers, and distribution lines used to supply power to consumers. Control rooms and communications systems coordinate the flow of electricity. All these electric grid components may be vulnerable to EMP.
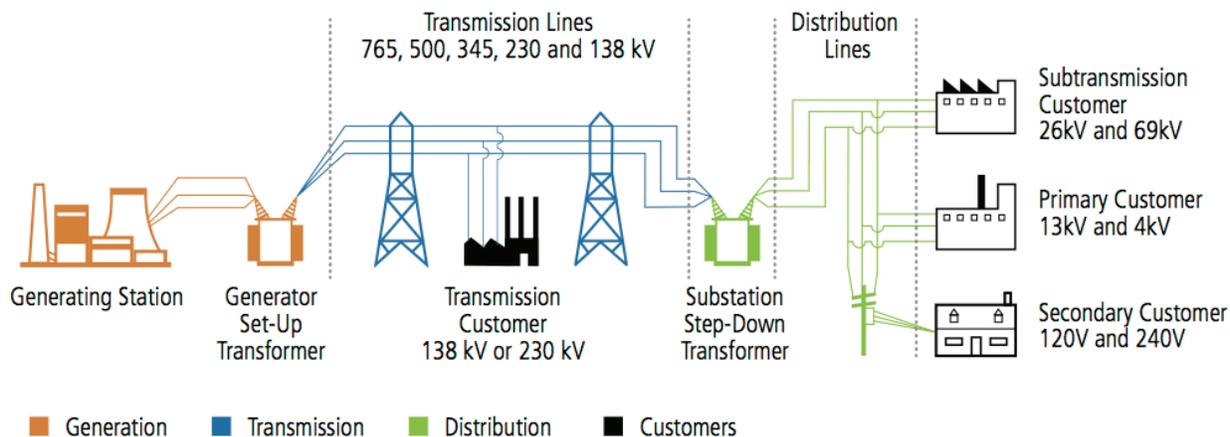
Figure 5: Electric Grid Generation, Transmission, Distribution, and Customers. Electricity is produced at generating stations, stepped up to high voltage for transmission, and then stepped down for distribution to homes and businesses. Generation and transmission assets supporting the high-voltage portions of the electric grid have the highest priority for EMP protections, because failures here can cause cascading collapse and prevent system restoration. Graphic credit: U.S. Department of Energy.

Generating Stations

Generating systems are essential to the electric grid and, therefore, their protection against EMP is of prime importance. Vulnerability to HEMP and GMD is expected to vary widely by generation technology. In this report we briefly address engineering challenges in protecting major categories of generation from EMP. More accurate cost estimates will require comprehensive engineering studies for each generation technology.

Technologies

In the United States, thermal generating stations supply baseload power. Technologies for thermal generating stations include natural gas, coal, oil-fired, and nuclear. These large facilities convert chemical or nuclear energy stored in fuel into heat that is deposited into a working fluid. This fluid is then used to drive a turbine-generator to convert heat into electricity. Roughly 80% of U.S. power generation comes from thermal power plants.

The share of renewable generation is growing due to concerns about climate change. Renewable technologies include hydroelectric, biomass, geothermal, wind, solar thermal, and solar photovoltaic. Hydroelectric generation relies on the gravitational potential of energy stored in water to drive a turbine-generator and is most common in the western watershed of the Rocky Mountains, California, and the Pacific Northwest. Biomass is important in locales with forest harvesting, such as in Maine and the southeast Atlantic Seaboard. Geothermal is used in the western portion of the United States. Wind and solar generation are currently small contributors to the U.S. generation mix but are growing in importance.

Natural Gas-Fired

Natural gas-fired plants tend to be recently constructed and almost always employ digital control systems vulnerable to the E1 pulse. Additionally, natural gas-fired plants do not have fuel stored on-site, but depend on pipelines with digital controls and, increasingly, electric-drive compressors. While the issue of EMP protection for fuel supplies is beyond the scope of this report, it should be a priority for future study.

Figure 6: Natural Gas-Fired Generation Plant. Photo shows a natural gas-fired generation plant with modular design. Use of open cable troughs (center) leaves control systems potentially vulnerable to the E1 pulse. Photo credit: Wikimedia Commons/Pro-Per Energy Services

Coal-Fired

Coal-fired plants are commonly large, enclosed structures with complex fuel systems for coal transport and pulverization. Many coal-fired plants originally built with analog controls resilient to the E1 pulse, have been retrofitted with vulnerable, digital controls. EPA-mandated emissions controls add another level of complexity and E1 vulnerability. However, coal-fired plants typically have 30-90 days of fuel stored on-site, a distinct advantage after disruptive EMP events.

Figure 7: Coal-Fired Generation Plant Complex. The John P. Madgett Station (left) and Alma Station (center, now decommissioned) in Wisconsin are coal-fired generation plants. The EMP vulnerability of coal-fired plants with complex fuel handling systems from the coal pile (center) to the furnaces near the smokestacks needs engineering study. Photo credit: Wikipedia/USGS.

Oil-fired plants have a range of sizes and combustion technologies, including steam turbine, combustion turbine, and internal combustion. These plants were typically built when oil was more cost-effective than natural gas and now near the end of their operational lives. Original designs included analog control systems less vulnerable to the E1 pulse, but updates can use digital controls. Larger oil-fired plants often have adjacent tank farms that store several weeks of fuel—an advantage after EMP events that may disrupt supply chains.

Figure 8: Oil-Fired Generation Plant. Wyman Station in Yarmouth, Maine is an 810 megawatt oil-fired generation plant. This plant was originally built in 1957-58 and has been updated several times with Unit 4, its largest unit, beginning operation in 1978. Pollution controls were installed in the early 2000s. EMP protection for pollution controls needs engineering study. Photo credit: Wikimedia Commons/NewTestLeper79

Nuclear

Nuclear power plants typically are enclosed in reinforced concrete structures that provide some degree of E1 shielding. Nonetheless, conductor penetrations into plants pose problems, because they introduce E1 transients to internal spaces and equipment. Also, the large power capacities of the plants and common use of single-phase GSU transformers make them vulnerable to the E3 pulse and GMD. Nuclear power plants have several years of fuel stored in the reactor core, a key resilience characteristic after EMP events. However, under Nuclear Regulatory Commission regulations, nuclear plants must be shut down when the bulk power system becomes unstable.

Figure 9: Nuclear Power Plant. Seabrook Station, New Hampshire is in a region susceptible to GIC during solar storms. The plant's 1,244 megawatt output requires use of single-phase GSUs. During a November 10, 1998 solar storm, vibrations induced by GIC caused a four-inch bolt to shake loose in the Phase "A" transformer. Subsequent melting caused loss of the transformer and several weeks of downtime. Photo credit: Creative Commons/Jim Richmond

Hydroelectric

Hydroelectric plants have simple electrical designs compared to other technologies. When most large hydroelectric plants were built in the first half of the 20th century, analog control systems were the norm. Analog controls are less vulnerable to the E1 pulse, especially when mechanical relays are used exclusively. While many hydroelectric plants have upgraded to digital control systems, some retain their original analog controls as a backup. Because the energy source for hydroelectric plants is water stored in a reservoir, their fuel supplies are resilient to disruption from EMP events.

Figure 10: Generator Hall at Grand Coulee Hydroelectric Dam. This photo of the Grand Coulee generator hall shows the original analog control panels to the left of the row of generators. Analog controls can still be used to run this plant. Instructions are communicated to manual operators by means of telephones on the control panels. This extremely simple system may continue to function following a HEMP attack. Photo credit: Creative Commons/Linda Moving Ahead.

Biomass

Biomass plants share basic engineering principles with other large thermal generators using combustion and, therefore, should have similar EMP vulnerabilities. Because most biomass plants are of recent construction, they have digital controls vulnerable to the E1 pulse.

Figure 11: Biomass Generation Plant. The 20 MW Savannah River Site Biomass Cogeneration Facility in South Carolina replaced a coal-fired plant. This plant burns forest residue. Note the complex fuel handling system in the foreground, which may be vulnerable to the E1 pulse. Photo credit: U.S. Department of Energy.

Geothermal

Geothermal plants commonly use wells to extract steam from underground heat sources to power turbine generators. Effective use of geothermal energy requires a system of pipes, sensors, and valve actuators. The digital control systems used at geothermal plants of recent vintage will be vulnerable to the E1 pulse.

Figure 12: Control Equipment at Geothermal Plant. This photo shows pipes and control equipment at the Steamboat Springs geothermal generation plant south of Reno, Nevada. Note the exposed sensor and actuator wiring that may conduct the E1 pulse into the green control cabinet. Buried wiring ducts exiting the control cabinet (bottom left) may also expose plant-level communications to the E1 pulse. Photo credit: Creative Commons/Rjglewis

EMP Vulnerabilities at Generating Stations

Overall, there is a lack of experimental data on EMP vulnerability of generating stations.[22] In general, we would expect large generating units to be vulnerable given reliance on digital control electronics. Sensing devices, actuators, and motors are commonly connected to central control rooms by long lengths of unshielded cable. Reliance on microprocessor-based components increases E1 vulnerabilities.[6]

Figure 13: Dual-Fuel Generation Plant. The Ravenswood dual-fueled generation plant (natural gas and oil) supplies power to New York City. Massive structures such as this will be very challenging to protect against EMP. Photo credit: Creative Commons/Rhododendrites

Some generating station technologies may be less vulnerable to EMP. Idaho National Labs claims that nuclear power plants may have resilience to EMP, though it does not expound on this claim.[22] Hydroelectric generators, less reliant on complex controls and employing older vintage equipment, are expected to have lower E1 vulnerability than fossil fuel generators. Fossil fuel generation, while potentially costlier to protect than hydroelectric or nuclear generation, is an important component of an EMP protection strategy due to its ubiquity and dispatchability.

Generator step-up (GSU) transformers are large power transformers designed to increase voltage from the level produced by a power plant's generator to transmission levels. For large baseload generators, GSUs are typically single-phase, full transformers operated at a high load factor. The primary E3 and GMD threat to power plants is expected to be the GSU transformers and associated high-voltage equipment in the adjacent switchyard.[18]

Figure 14: Generator Step-Up Transformers at Arizona-Nevada Switchyard for Hoover Dam. Single-phase generator step-up transformers raise voltage for long-distance transmission. During HEMP and GMD events, the transmission lines from Los Angeles to the switchyard can conduct geomagnetically induced currents into the windings of the transformers, causing overheating and harmonics. Without use of neutral ground blocking devices, harmonics can also be conducted into the dam's massive generators, causing vibrations and heating. Photo credit. Wikimedia Commons/Deborah Dobson-Brown.

E1 Vulnerability

As with other large power transformers, some GSU vulnerability to E1 is expected, but is presently uncertain due to lack of test data. A large concern is failure of low-voltage components used for active cooling of the transformer; another concern is winding insulation failure during the E1 pulse.

E3 and GMD Vulnerability

GSUs are expected to be at risk of oversaturation from E3 and GMD, given the prevalence of high load factors and single-phase configurations at generating plants. These transformers are designed with low winding resistance and are located within extra high-voltage (EHV) grid with long, low resistance conductors, causing them to carry the highest GIC. [18]

In the event of catastrophic failure, fire at GSU transformers could ignite the oil coolant, in this case leading to widespread damage to the generation plant beyond the GSU.[3] Alternatively, if the transformer continues to operate during oversaturation, resulting harmonics could also damage the connected generator.

During the 1989 solar storms, thermal damage occurred to multiple, single-phase GSU transformers at the Salem nuclear plant. The U.S. Nuclear Regulatory Commission (NRC) reported that the damage sustained by the transformer occurred after just a few minutes of GIC exposure.[11][18]

Generators

Generators are large electro-mechanical rotating machines that convert mechanical energy into electrical energy. In thermal plants, a heated working fluid is expanded through a turbine causing the turbine to rotate. This rotation is transferred to the generator along a shaft. The generator, itself, is comprised of conductive coils within a magnetic field. Rotation of the coils within the magnetic field induces an electric current in the windings via Faraday's law. Low-voltage buses connected to generator windings conduct current to GSU transformers, where voltage is increased to transmission levels.

E1 Vulnerability

While windings of the generators may conduct the E1 pulse, generator stators, rotors, and frames are built to be robust and may not sustain damage. However, damage or upset to a generator's control electronics from E1 is likely. Future engineering study of generator vulnerability to E1 is needed.

E3 and GMD Vulnerability

Generators are protected from direct exposure to GIC by use of delta-wye transformer connection employed in GSUs. Harmonics caused by GIC in transformers, however, can create overheating and vibrations in generators. Mechanical vibrations could reduce generator life, but are unlikely to cause immediate failure.[3][11][21]

Figure 15: Generator Driven by Steam Turbine. Steam turbine (foreground) drives the electric generator (background). Generators can be vulnerable to overheating and vibration from harmonics caused by the E3 pulse and GMD. Photo credit: Wikipedia/ Siemens Pressebild

Control Systems

Generating stations use Supervisory Control and Data Acquisition (SCADA) and programmable logic controllers (PLCs) extensively to enable plant automation, centralized monitoring, and control. Plant SCADA systems are wired by either fiber or copper cabling.

E1 Vulnerability

For cabling in generating stations, induced voltages may be as high as 70kV in a small proportion of cables.[4]

Power plants use PLCs extensively. These are particularly susceptible to upset and damage from E1 and can fail at relatively low levels of E1-inducted current. Generating station PLCs appear to be more vulnerable than relays used in transmission substations, as PLCs are not designed with the same degree of electromagnetic protections due to the lower voltage environment.

Figure 16: Control System Cabling for Combined Cycle Power Plant. Combined cycle power plants often have open-air designs with exposed control system cables running in open troughs between plant components and buildings. Note the exposed cable troughs at the center of this photo taken at a gas-fired generation plant. Photo credit: Foundation for Resilient Societies

E3 and GMD Vulnerability

Since the conductors associated with generating station controls and embedded systems are short relative to the E3/GMD wavelength, these systems are not expected to be directly vulnerable to E3 or GMD. Uninterruptible power supplies for generating station controls are known to be susceptible to upset and damage from E3/GMD harmonics.

Transmission Lines

Transmission towers and conductors are expected to be resilient to EMP. However, during 1962 Soviet EMP tests over Kazakhstan, transmission line insulators experienced flashover from the E1 pulse, causing the lines to fall to the ground. It is not known if modern insulators have this same vulnerability. Engineering study of insulator EMP vulnerability is needed.

Figure 17: Transmission Tower, Insulators, and Lines. A common method of constructing high-voltage transmission lines is to use steel towers that support aluminum conductors. Ceramic insulators isolate the conductors from the towers. During the E1 pulse, an electrical arc may be established over the ceramic insulators to electrical ground, persisting after the pulse ends and causing catastrophic insulator failure. Vulnerability of modern insulators needs engineering study. Photo credit: Pixabay.

Substations

Substations, where power flow is controlled and often reduced in voltage, are the intermediate nodes of the transmission network. Design and configuration of substations vary widely. Equipment at substations commonly includes step-down transformers to reduce voltage, circuit breakers to interrupt and reroute power, instrumentation devices to sense power flow, relays to control circuit breakers and protect transformers from overload, and SCADA devices to permit remote operation. Substation communication, data processing, and control devices are often enclosed within small, on-site buildings— "control houses" or "control huts." Some substations have voltage support devices such as capacitors, reactors, and SVCs.
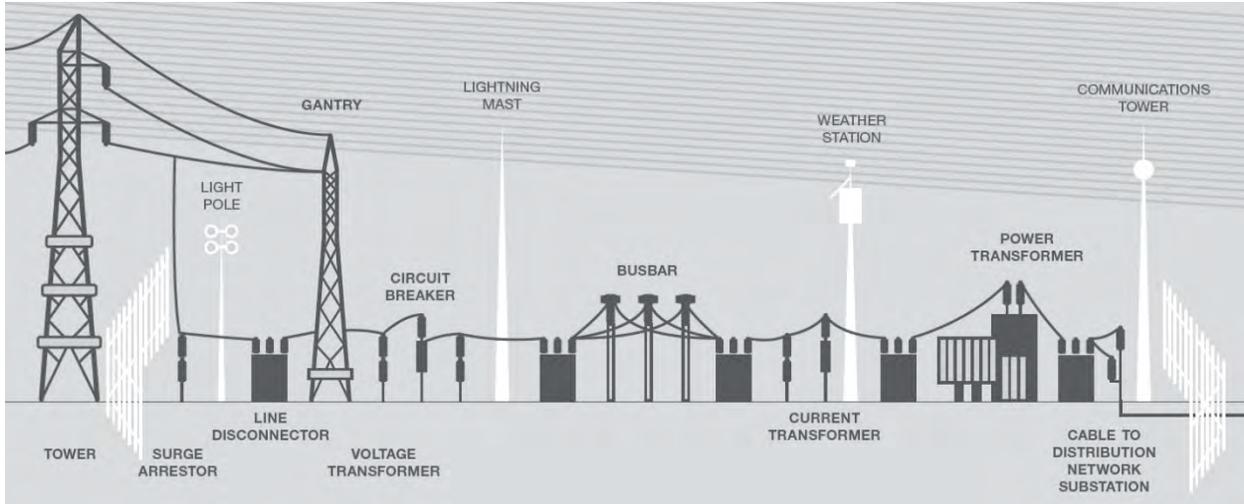
Figure 18: Power Flow through Notional Substation. When high-voltage power enters a substation, it is controlled by line disconnectors and circuit breakers, routed by busbars, sensed by current transformers, and stepped down by power transformers before exiting to distribution networks. Graphic credit: ElectraNet

Figure 19: Bulk Power System Substation. Substations for the bulk power system transform high voltage electricity into lower voltages for homes and businesses. Circuit breakers at the left section of substation control power flow into high voltage transformers at the right. Communications for the substation are carried by microwave radio dishes on the tower at the rear. Open-air designs such as this expose substation components to the E1 pulse from HEMP. Photo credit: Creative Commons/vaxomatic

Substations can be small, with only a single set of circuit breakers and transformers. However, long-distance electricity transmission for the bulk power system often requires large substations with dozens of components arrayed over an acre or more of land. Substations are commonly an open-air design, although entire substations in urban areas may be enclosed in buildings.

Power Transformers

Step-down power transformers located at transmission substations decrease voltage from transmission levels to distribution levels.

Figure 20: Substation Power Transformer. Three-phase substation power transformer steps down electricity voltage for local distribution system. Note the connected circuit breaker with swinging control housing doors near transformer. The control circuits for both transformers and circuit breakers are likely to be vulnerable to the E1 pulse from HEMP. Photo credit: First Energy.

Although highly efficient, transformers generate significant amounts of heat from losses inside the transformers. The E3 pulse and GIC from GMD change flux distribution within transformers, increasing losses. Even relatively brief periods of overheating can damage a transformer's internal windings and insulation.[11]

Replacing large power transformers is a lengthy and logistically challenging task. Typical replacement lead times range from one to three years under normal conditions in part because these transformers are usually custom designed. Most large power transformers now used in the United States are produced abroad. Domestic supply has been increasing in recent years but faces supply chain bottlenecks. For example, high-grade electrical steel, one of the primary material components of a transformer, has only

a single domestic producer. Transportation of a transmission-scale transformer to the substation is, itself, a challenge; it can weigh up to 400 tons and requires specialized rail cars or vehicles to move.[9] [16]

HEMP and GMD-induced currents can cause transformers to overheat, leading to degradation and potentially to immediate failure, especially should the electric grid and transformer remain online long enough for damage to occur. Assessing the risk of immediate damage to transformers during a HEMP or GMD event will require additional engineering study.

During HEMP and GMD events, transformers produce harmonics and increase reactive power consumption, which can cause grid collapse from relay tripping and low voltage. A HEMP or GMD event can damage transformers indirectly through overload conditions experienced during an uncontrolled grid collapse.

E1 Vulnerability

Published data on the vulnerability of large power transformers in E1 environments is sparse. However, some researchers assert that transmission transformers can withstand the E1 pulse without damage, since the transformer is a passive device without microelectronics and designed to operate at high-voltages[17] The Congressional EMP Commission, however, warned that E1-induced arcing might damage insulation for internal transformer windings.

Of greater concern for E1 vulnerability are the low-voltage sensor and control lines connected to transformers.[4] A loss of proper relaying could leave transformers vulnerable to damage subsequent to the E1 pulse, such as the following E3 pulse. The electronics for relay systems are typically located within the substation control house and can, therefore, be protected separately from the transformer, itself.

Figure 21: Cooling Components for Power Transformer. Power transformers commonly have oil pumps, radiators, and cooling fans. The exposed electrical wiring for these fans will conduct the E1 pulse into control circuitry for the transformer. Photo Credit: T&D World

Cooling equipment for power transformers is controlled by microprocessors vulnerable to E1 damage. Without active cooling, the transformer would be unable to operate at design capacity. With properly functioning sensors and relays, damage to cooling controls may not cause transformer damage but could impede grid recovery by constraining transmission capacity.

Transformer monitoring systems are becoming increasingly common. These systems monitor temperature, pressure, and gas bubble generation in the cooling oil. For some transformers, GIC can also be monitored. The digital circuitry for monitoring systems can be vulnerable to the E1 pulse from HEMP. At generation plants, alarm signals from transformer sensors may be used to shut down generators during HEMP and GMD events.

Figure 22: Transformer Monitoring System. Transformer monitoring systems collect and analyze data, presenting alarms when abnormal conditions are detected. While data from these monitoring systems would be extremely useful during a HEMP or GMD event, the copper wiring used for sensor cables can conduct the E1 pulse into monitoring system cabinets. Photo credit: GE Digital Energy

E3 Vulnerability
Published literature and test data is lacking on high-voltage (HV) and EHV transformer vulnerability to the E3 pulse from HEMP. Significant experience does exist for transformer operation in the similar GMD environment, though some differences between the threats are pertinent. From GMD experience, it is known that GIC, common to both the GMD and E3 pulses, can cause transformer overheating and

vibration. E3 also causes transformers to produce harmonics and increase reactive power consumption. Harmonics further contribute to heating and can adversely affect other components of the grid, possibly leading to cascading collapse. Increasing reactive power consumption leads to voltage drops and decreases availability of active power, which can also collapse the grid.

The E3 pulse induces currents up to hundreds or thousands of amps in long power lines for between ten seconds and four minutes.[17] This low-frequency GIC appears as a quasi-DC bias compared to the typical 60 Hz power flow. The transmission lines conduct this GIC to transformers. If the quasi-DC bias combined with the existing power flow is sufficiently high, the transformer will experience half-cycle saturation, leading to bulk and localized overheating, production of harmonics, and an increase in reactive power consumption.[18]

The effects of overheating from the E3 pulse are cumulative and will degrade transformer life, but there is dispute on whether large numbers of transformers will immediately fail. According to an Electric Power Research Institute (EPRI) report that relied on mathematical simulations and non-destructive testing of only two transformers, the brevity of the E3 pulse may limit internal heating.[17] Other analysis suggests saturation quickly follows GIC injection and debilitating damage from internal heating can occur on E3 time scales.[3][11][19]

Production of harmonics from the E3 pulse could lead to transformer relay misoperation and protective tripping of transformers and generators.[3] Given the wide-area effects of E3 and GMD, the near simultaneous tripping of many transformers could precipitate a system collapse that would expose transformers remaining online to damaging overvoltages. Harmonics also contribute to transformer overheating[9] and can damage other grid components, such as devices to support reactive power.

Heightened reactive power consumption by transformers reduces real power, potentially leading to an unstable grid and a damaging, cascading collapse. For a given level of GIC, single-phase transformers and high-voltage transformers experience a greater increase in reactive power consumption than similar transformers of three-phase configuration or lower voltage.[3]

Because transformer damage occurs via oversaturation, vulnerability is dependent on the transmission system loading at the time of the event. Transformers operating closer to design capacity are at greater risk. Transformers on higher voltage lines with lower resistance and in single-phase configurations are also more susceptible to damage.[8] These effects combine to make GSU transformers for large, baseload power plants particularly susceptible. GSU transformers typically operate continually near design capacity, connect to high-voltage lines, and are often single-phase due to the difficulty of manufacturing and moving three-phase transformers of this size.

Step-down transformers typically found in substation nodes are less likely to be operating near design capacity at any given time. These transformers must be sized to accommodate peak electrical demand, but typically are loaded at less than 50% of capacity. The automatic disconnection of some transformers from the grid following the E1 and E2 pulses, however, would result in more power being rerouted through remaining transformers, increasing their vulnerability. While GSU transformers are generally more vulnerable, the autotransformer design used for many substation step-down transformers has tertiary windings vulnerable to localized overheating.[17]

GMD affects transformers similarly to the E3 pulse. As with E3 pulse, the potential for bulk and localized heating arises from transformer oversaturation. GMD events have lower intensity but longer duration than E3. As a result, GMD allows more time for heat to build up in transformer components.

The solar storm of March 1989 clearly illustrated the vulnerabilities of transformers to GMD. Across the Hydro-Quebec grid, harmonics from oversaturated transformers caused multiple SVCs to trip. This loss of reactive power supply, combined with the increased reactive power draw from saturated transformers, led to a cascading collapse. Overvoltage conditions created by the uncontrolled collapse damaged two GSU transformers at the La Grande 4 hydro plant.[20]

Figure 23: Failure of Salem Nuclear Plant GSU Transformer. Pictured below is one of the three single-phase transformers at the Salem Unit 1 nuclear plant. This transformer failed shortly after the March 13, 1989 solar storm. Geomagnetically-induced currents in transmission lines conducted into the transformer windings, causing saturation and overheating. Forensic examination showed charred insulation and melted windings. Photo credit: PSE&G.

No transformers failed during the March 1989 storm as a direct result of overheating. Routine inspection after the storm, however, revealed the GSU transformers of Salem Nuclear Power Plant Unit 1 had sustained severe damage. Overheating burned insulation and melted copper conductors. Damaged transformers had to be removed from service.[20]

While damage to the Salem Unit 1 transformer was most obvious, the storm may have contributed to widespread life-shortening of other high-voltage transformers, including at Salem Unit 2 and at Maine Yankee. In the two years following the March 1989 storm, 18% of U.S. nuclear power plants experienced GSU failures, much higher than would be anticipated absent a common cause.[7] Following the storm, Allegheny Power System also reported damage to 36% of its EHV transformer fleet from overheating.[11]

Circuit Breakers

Circuit breakers are designed to interrupt current on live transmission lines. The ability to break circuits is necessary to control grid flows, isolate damaged equipment for maintenance, and protect equipment in the event of a fault. Given their importance for grid operation, EHV substations are typically arranged in a breaker-and-a-half configuration in which all circuit breakers share an online spare.

Interruption of the circuit at high voltage leads to arcing between the electrical contacts. Circuit breakers use various insulators to extinguish the arc, including oil, air, and inert gas. The optimal time to interrupt the arc is at instants of zero-current that occur twice on an AC cycle.

Figure 24: Substation Circuit Breaker. This gas-insulated circuit breaker interrupts all three phases of high voltage electricity. Note the exposed control cables underneath the breakers that would conduct the E1 pulse into the gray-colored circuitry cabinet. Photo credit: The Toledo Blade.

An E1 pulse may damage the low-voltage circuits used to signal and operate the circuit breaker. Testing and rigorous analysis of this vulnerability are missing from the EMP literature.

Both the E3 pulse and GIC from GMD impose a DC bias on high-voltage lines. This DC bias could eliminate the zero-current event on which AC circuit breakers depend to extinguish arcing. Attempting to operate the breaker in the absence of a zero-current crossing could result in catastrophic failure of the breaker. Rapid voltage fluctuations during a GMD event could also lead to damaging current restrikes.

E1 Vulnerability
Theoretical analysis of circuit breakers exposed to E1 also appears to be a gap in the EMP vulnerability research and literature. Our interviews with industry experts revealed disagreement on the anticipated effects of an E1 pulse on circuit breakers.

As with other high-voltage equipment, some experts believe the high-voltage components of circuit breakers will withstand an induced E1 pulse, since these components are exposed to even higher voltages during normal operation. Circuit breakers, however, also rely on small motors, pressurized components, recharging springs, release solenoids, and other control circuitry to break the high-voltage contacts. Since these components operate at low voltage, experts suggested E1 could damage these components, most especially their electrical controls. In instances where E1 damages the recharging system but energy is still stored mechanically within the breaker, breakers may be able to operate once or twice after the E1 event. Some circuit breakers have control logic at the breaker to coordinate the break with the zero-current crossing. Control microprocessors could be vulnerable to the E1 pulse. Disruption of control logic could lead to the breaker attempting to break when zero-crossing may not exist during the subsequent E3 pulse, which could cause catastrophic breaker failure.

Other experts, however, believe low-voltage portions of some circuit breakers may not be vulnerable to the E1 pulse. The cheapest and most common circuit breakers are dead-tank breakers, in which components inside the metal tank may be sufficiently protected from an E1 pulse.

In summary, while the controls of some circuit breakers may be resilient to the E1 pulse, this is not universally true for all circuit breakers. Figure 25, for example, shows an open cabinet for a high-voltage circuit breaker. This metal cabinet with swinging doors and multiple cable penetrations would not provide an effective E1 shield to any enclosed digital components.
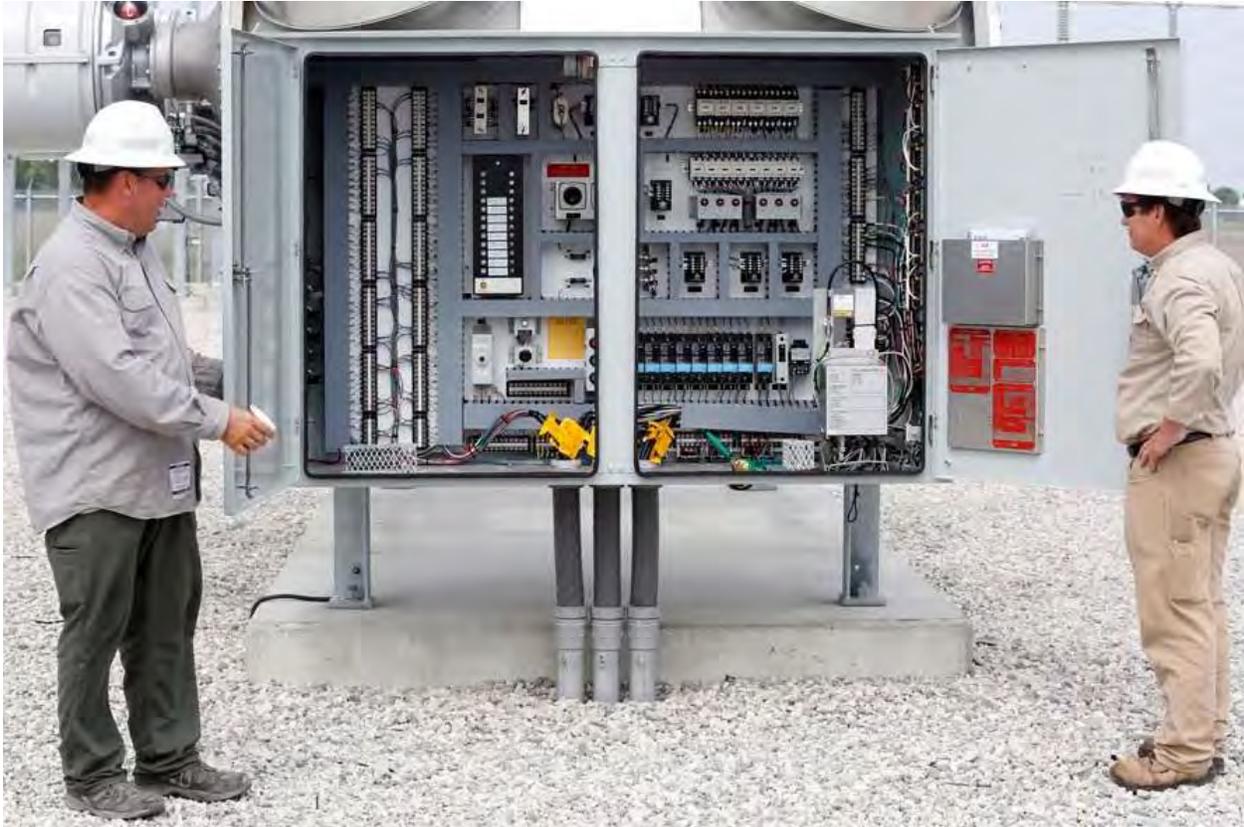
Figure 25: Substation Circuit Breaker Cabinet. Cables exit the underside of the circuit breaker control cabinet, passing underground to relays located in a substation control house. Even buried cables would conduct the E1 pulse into the cabinet and into the relays. Photo credit: The Toledo Blade.

E3 and GMD Vulnerabilities

While data on high-voltage circuit breakers in HEMP environments is not publicly available, circuit breakers have been exposed to GIC during solar storms. We are not aware of any circuit breaker failures during GMD events, though the North American Electric Reliability Corporation (NERC) reports that circuit breakers have been "impacted" by previous storms. Interviewed experts agreed circuit breakers could fail during E3 or extreme GMD events.[9] Without controlled testing of circuit breakers to failure, however, it is difficult to assess the degree of circuit breaker vulnerability.

AC circuit breakers depend upon instances of zero-current (as happens twice a cycle in AC circuits) to disconnect high-voltage contacts. If the GIC greatly exceeds the current on the line, the DC bias could remove any occurrence of a zero-crossing. Attempting to break a live circuit without a zero-current crossing could result in a sustained arc lasting for several seconds or minutes until the circuit breaker is damaged. In such a situation, circuit breaker control of bulk power flows within the transmission system would be lost.[3 9 19 21]

Circuit breakers on lines with low loadings would be most susceptible to zero crossing failure as even a weak GIC can eliminate the occurrence of zero-current when line current is small. The relationship between vulnerability and loading for circuit breakers is thus opposite of that for power transformers.

Power transformers are more likely to experience saturation and overheating while at high loadings, whereas circuit breakers are more likely to lose zero-current crossings while at low load.

Additionally, attempting to operate circuit breakers during highly variable GIC could lead to catastrophic damage due to presence of high current or voltage transients. Strong voltage transients could cause arc restrikes and chopping current, resulting in damage to breakers and connected devices.[11]

Instrument Transformers

Instrument transformers convert grid current (current transformers) or voltage (potential transformers) to a proportional low-power signal used for relaying or metering. Essentially, instrument transformers are the sensors that read grid conditions. Instrument transformers can be installed in the bushings of transformers or as part of circuit breaker assemblies, though they can also be deployed as stand-alone assemblies. Many instrument transformers have an online backup.

Some interviewed experts expect the low-voltage sides of instrument transformers to be vulnerable to the E1 pulse. The high-voltage sides are expected to withstand the E1 pulse. Instrument transformers may be driven into saturation via their connection to the high-voltage line and GIC. Additionally, harmonics from the power transformer will be conveyed through the instrument transformers to the relays.[17] Should saturation occur, instrument transformers are not expected to fail immediately and have additional resiliency through redundant deployment, though the distorted signal resulting from saturation could lead to relay misoperation.

Figure 26: Instrument Transformers in Substation. Instrument transformers sense voltage and current by means of the transmission line conductor passing through an annular core wrapped with copper windings. All three phases of current pass through this inline set of instrument transformers to the right of the power transformers. Photo Credit: Pixabay.

E1 Vulnerability

No results of instrument transformers against E1 pulses are available in open literature. In a published report, SARA Corporation asserted that insulation in transformer primaries should withstand the

conducted E1 pulse, since these windings connect directly to the high-voltage grid. Conductors connecting the low-voltage sides of these transformers to the substation control house will be sufficiently long to conduct the maximum E1 pulse, possibly necessitating protection of the secondary windings. If required, protection of secondaries with metal oxide varistors (MOV) or filters is likely to be feasible, but no tests have been conducted.[17] If instrument transformers have digital circuitry for analog to digital signal conversion or amplification of signals, this circuitry is likely to be vulnerable to the E1 pulse.

E3 and GMD Vulnerabilities

We do not expect that instrument transformers will be vulnerable to permanent damage from E3 and GMD, although saturation from GIC may cause erroneous readings. Further engineering study of instrument transformers under GIC conditions is needed.

Voltage Regulation Devices

Capacitor banks, reactors, and SVCs are used to stabilize voltage by managing reactive power on the electric grid. Reactors consume excess reactive power and are typically disconnected from the grid, except for situations such as black starts when generation and load mismatch may cause an excess of reactive power. SVCs combine capacitors and reactors along with fast automated switching to provide finer reactive power control in both directions. Loss of reactive power devices can lead to voltage swings and cascading collapse in power systems.

Capacitors

Capacitors provide additional reactive power to the grid and are typically located at the grid edge to counteract degradation in power delivery efficiency caused by the high inductance of transmission lines and rotating machinery loads. Capacitors in series with transmission lines can protect against the GIC caused by the E3 pulse and GMD.

Figure 27: Substation Capacitor Bank Capacitor banks are installed in substations to provide reactive power support. Substation capacitors operate at the voltage level of the connected transmission line and, therefore, are expected to be resistant to the high voltage of the E1 pulse. Photo Credit: Wikimedia/Phillipe Mertens

E1 Vulnerability

Since substation capacitors are designed to operate at transmission level voltages, we expect capacitors may accommodate the E1 pulse without damage; but testing will be required. The E1 pulse could cause breakdown across capacitor plates resulting in damage. E1 could also affect the relay systems controlling capacitor operation.

E3 Vulnerability

Substation capacitors can be tripped offline by a reversal in GIC flow during GMD events. This could cause loss of capacitors at a lower level than would necessitate relay operation to protect against overcurrent.

GMD Vulnerability

In addition to the issues of overcurrent exposure for E3, the fluctuations in the DC power flow experienced during a GMD event introduce issues for capacitors not experienced during E3. A large GIC can induce reactive power compensation from capacitors, but then swing to a negligible GIC causing overvoltage and leaving the capacitor bank unavailable for several minutes.

Shunt Reactors

Shunt reactors reduce reactive power in the electric grid and are typically located in substations or near generating stations.

Figure 28: Substation Shunt Reactor Air core shunt reactors at a substation in Montana near the Noxon Rapids hydroelectric generation dam are designed to absorb reactive power. The spinning generators at hydroelectric plants produce large amounts of reactive power; shunt reactors balance this power during grid restoration. While shunt reactors operating at high voltage may be resilient to the E1 pulse, the vulnerability of their control systems needs engineering study. Photo Credit: Creative Commons/VARsity

Shunt reactors are typically disconnected by a mechanical switch from the grid and are brought online following outages to compensate for low load conditions. Even if connected to the grid, the basic structure of the reactor is expected to be resilient to EMP. However, if the switching systems for the reactors have digital components, these components could be vulnerable to the E1 pulse.

Static VAR Compensators

SVCs are faster and more flexible reactive power control systems than mechanically switched capacitors and reactors. As reactive power needs change due to leading or lagging power factor, SVCs switch capacitors and reactors in and out of the active circuit. The sensing of power factor and control of capacitor and reactor switching depends on digital circuitry. As a result, SVC control systems may be vulnerable to E1 damage.

SVCs and their capacitors might be damaged by E3 or GMD if the event causes sufficient overvoltage. Proper relaying and redundant protections mitigate this risk, but the tripping of the SVCs or capacitors would still contribute to system collapse. Harmonics generated in transformers from E3 and GMD can also cause SVC relay misoperation, tripping SVCs offline when they are most needed by the electric grid.

Figure 29: Static VAR Compensator Capacitor banks are on the left of the facility reactors in center. The building on the right contains controls for switching capacitors and reactors to provide lagging or leading power factor. The digital controls for SVCs are likely to be vulnerable to the E1 pulse. Photo Credit: T&D World.

E1 Vulnerability

SVCs rely on digital controls and actively cooled thyristor valves housed separately from the main substation control house. These digital control systems may be vulnerable to E1 depending on the efficacy of protections designed for other electromagnetic threats against the E1 pulse. We are, however, unaware

of any testing specific to SVC controls in E1 environments. SVCs have long cables connecting the controls to components in the substation yard.

E3 and GMD Vulnerabilities

SVCs can be damaged from overcurrent occurring from the quasi-DC bias induced by E3 and GMD. Proper relays can trip the SVC to protect it, but this may remove needed voltage support from the rest of the system. The fast-acting reactive power management of SVCs are of increased importance during an E3 or GMD event due to the increase in reactive power consumption in saturated power transformers.

The loss of SVCs due to protective relaying was a primary contributor to the Hydro-Quebec blackout. In this event, relays misoperated in response to harmonics introduced to the signal from transformer saturation caused by the ongoing solar storm. NERC determined that, in this case, SVCs could have remained operational without damage and proper relaying may have averted the blackout.[9] [21] Nonetheless, E3 and GMD events can produce sufficient overcurrent to trip SVCs and, in such instances, improved relaying would not necessarily protect the system from collapse.[3]

Control Houses

Substation control and communications equipment are typically located within control houses or huts, commonly constructed from metal or concrete. Because most control houses are not designed as for E1 protection (shielding plus penetration treatments), EMP field and current attenuation they provide can be minimal. Thus, equipment in the interior of the control house will likely be vulnerable to the E1 pulse.

Figure 30: Exterior of Substation Control House. Sheet metal is often used to construct substation control houses. Note the HVAC unit hung on the exterior wall of the control house; these units can have digital circuitry vulnerable to the E1 pulse. Photo credit: Creative Commons/Paul Chernikhowsky.

E1 Vulnerability

Relays and other control electronics within control houses can be susceptible to E1-pulse. Because equipment in control houses produces heat, air conditioning or other active cooling is almost always necessary. Without temperature control, relays and other equipment in the control house will experience failure or shortened operational life. The digital controls for this cooling equipment can be vulnerable to the E1 pulse.

E3 and GMD Vulnerabilities

Because the HVAC equipment for control houses does not connect to long conductors (such as transmission lines), it is not directly vulnerable to E3 and GMD. However, during tests at the Idaho National Laboratory, air conditioning connected to power lines with E3-induced harmonics suffered misoperation. Unlike relays and other equipment within substation control houses, HVAC does not have the benefit of conditioned power from uninterruptible power supplies.

SCADA

SCADA systems allow control and monitoring of large systems via digital connections. A typical SCADA system is essentially a network of digital processors, sensors, and controls connected to a central unit. The hardware components that comprise a SCADA system use many of the same digital technologies as computers with Ethernet connections. SCADA systems monitor and coordinate substations from a central control center. Damage to SCADA could result in a loss of operational awareness or loss of central control of substations.

Figure 31: Rack Populated with Relays and SCADA in Substation Control House. SCADA, relays, and other digital equipment are typically contained in substation control houses. The E1 pulse, conducted into equipment interfaces, can cause upset and permanent damage. Photo credit: The Toronto Blade

E1 Vulnerability

Since SCADA units are commonly comprised of microprocessors connected to conductive cabling, they are susceptible to E1 damage. The Congressional EMP Commission conducted testing and analysis on SCADA systems and concluded SCADA represents "the key vulnerable electronic system" to EMP. Free field tests resulted in incorrect readings of process status as well as some instances of damage to SCADA sensing equipment. Ethernet connection ports were particularly vulnerable. Idaho National Laboratory also notes, "unshielded embedded systems [such as SCADA] will likely be damaged by an EMP." [22]

Attenuation from the control house or control cabinet (in the case of remote terminal units (RTU) located in the switch yard) may provide some protection to SCADA devices, but cabling running through the switchyard connecting SCADA units would direct E1 pulses into terminals. The Congressional EMP Commission also conducted current injection testing to simulate this effect. The Commission found that while SCADA systems are well protected against fast transients up to the level specified by existing electromagnetic interference standards, SCADA failed when subjected to the stronger transients expected from an E1 event.

Metatech Corporation tested electronic systems against simulated E1 environments, but only a single brand of SCADA communication unit. The Schweitzer Engineering Laboratories (SEL) unit tested withstood the E1 fast transient, but other brands and designs of SCADA remained untested.[4]

E3 and GMD Vulnerabilities

SCADA units are not directly connected to the transmission lines that couple to the E3 or GMD. The cables connecting SCADA units, while long from an E1 coupling perspective, are not sufficient in length to couple E3 or GMD currents.

Relays

Protective relays at substations assess grid stability and isolate equipment from line surges, faults, and other conditions that could cause damage. Potential transformers and current transformers are the sensors for these relays. Lines connecting protective relays to substation sensors typically run a hundred feet or more through the yard and into the control house.

Upon detection of conditions that could damage equipment, such as excessive voltages or currents, protective relays open circuit breakers to remove exposed equipment from service. Relays are commonly programmed to reclose the breaker when transients clear on their own.

The flexibility of digital relays allows them to combine protection against multiple threats in a single unit and incorporate greater intelligence into relay decision-making compared to their analog counterparts. This flexibility, however, depends on solid-state circuitry that is typically more susceptible to electromagnetic threats.

Electromechanical relays are more robust than solid state digital relays. They serve the same protective function as digital relays but utilize analog operations. Electromechanical relays have been widely replaced with newer digital relays in high-voltage substations but are still present in a minority of substations.

Figure 32: Vintage Electromechanical Relay. Electromechanical relays such as the General Electric model pictured here were once widely installed in substations, but now represent a minority of relays in use. Testing shows these devices are resilient to the E1 pulse. Photo credit: Pinterest/MCBIA Sales.

Digital Relays

Digital relays contain microprocessors sensitive to the high amplitude pulse of E1 and connect to long cable leads from the switchyard that can conduct the pulse. Relays, however, are designed to operate in environments with electromagnetic transients. Some testing suggests that robust relay designs already have sufficient protection to avoid E1 damage. Other tests suggest for some digital relays E1 resiliency could benefit from improved shielding and signal filtering. Even if relays do not sustain damage from the E1 pulse, the pulse could contribute to relay misoperation, which, in turn, could result in catastrophic damage to high-voltage grid components.
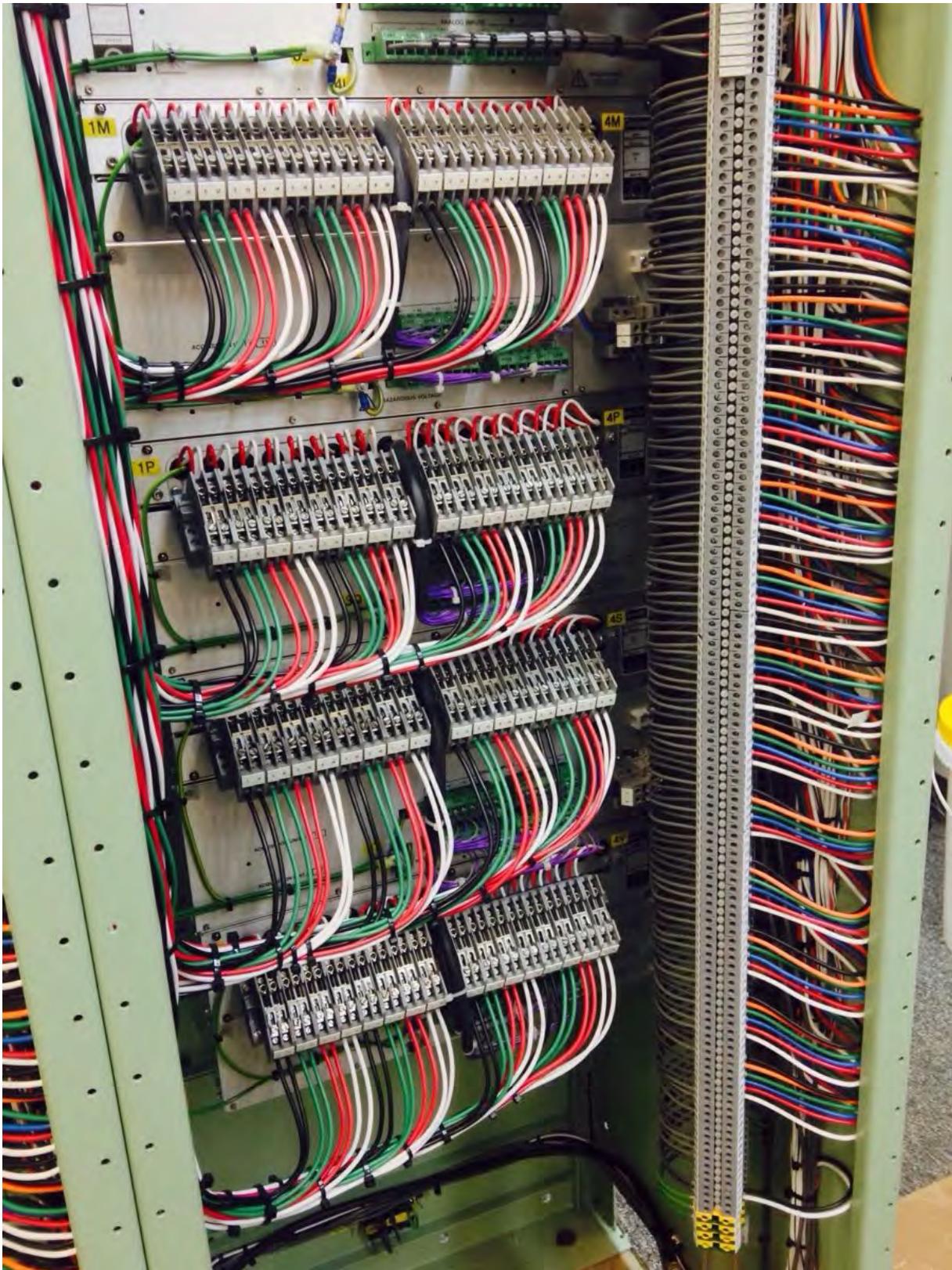
Figure 33: Cabling for Substation Relays. Plastic-sheathed, copper-conductor cabling can conduct the E1 pulse into racked equipment, causing upset and damage. Photo Credit: Pinterest/imgur.

E1 Vulnerability

Multiple researchers have conducted tests on digital relays to assess their vulnerability to electromagnetic fields and the conducted E1 pulse. The Congressional EMP Commission conducted tests on digital relays and reported these devices were the "most robust of any electronic device tested" but were liable to upset. Metatech conducted its own tests on SEL brand digital relays. Metatech's pulse current injection tests resulted in no damage to tested relays through the strongest pulse tested with a peak voltage of 8kV but upsets repeatedly occurred.[4]

Engineers from SEL also conducted HEMP tests on SEL relays. The SEL units withstood all tests, leading the study's authors to conclude SEL and other digital relays that comply with IEC 60255-26 or IEC 60255-27 or have a 5kV impulse voltage withstand are HEMP resilient.[23] At least one researcher highly criticized the SEL methodology used in this study.[24]

SARA conducted electromagnetic field and pulse tests on three brands of digital relays. SARA reported all but one digital relay was eventually damaged via pulse current injection when used without a protective MOV. Failures began with injected currents as low as 200A. Implementation of MOV protection greatly improved performance with only one unit failing and only at 2500A—the highest current injection tested.[17]

Despite the resilience of some relay designs to the E1 pulse, concurrent failure of even a small proportion of substation relays during an EMP event could cause loss of control of the bulk power system and potential system-wide collapse, including damage to high-voltage grid components.

E3 and GMD Vulnerability

Because relays do not connect directly to long transmission lines, they are expected to be resilient to damage from E3/GMD.[17] Harmonics resulting from transformer saturation will be transferred to the relay through current transformers and could result in misoperation. Newer digital relays with improved logic can detect the presence of harmonics and continue proper operation in the E3 environment.[3]

Electromechanical Relays

Given their hard-wire design, electromechanical relays are robust against damage from HEMP and GMD. The absence of signal filtering, however, leaves electromechanical relays more susceptible to misoperation than their digital counterparts.

E1 Vulnerability

Several tests of electromechanical relays demonstrated resiliency to E1 damage. The Congressional EMP Commission tested electromechanical relays and found them immune to damage up to the highest test levels. Metatech conducted pulse testing on two electromechanical relays up to 8kV level (injector limit) without failures.[4] SARA also tested electromechanical relays up to 8kV without signs of damage.[17]

E3 and GMD Vulnerabilities

Electromechanical relays are expected to be immune from E3/GMD damage but may be susceptible to misoperation.[3] Electromechanical relays are designed to operate on the fundamental frequency and have limited ability to discriminate among higher-order harmonics.[25] Digital relays, however, can be programmed to be resistant to tripping during E3 or GMD events. As a result, electromechanical relays have a greater probability of misoperation during E3 and GMD than well-designed digital relays.[9]

Uninterruptible Power Supplies and Battery Chargers

Substations are powered using auxiliary power from the grid stepped down and processed through an uninterruptible power supply and battery system. In the event of a loss of grid power, the battery system remains available to power the substation, typically for a duration of eight hours.

Figure 34: Uninterruptible Power Supply and Battery System. UPS and backup battery systems supply power to low-voltage substation devices, including circuit breakers, relays, and other control devices. Power leads into the UPS will conduct the E1 pulse and harmonics resulting from E3/GMD; malfunction or equipment damage could result. Photo Credit: BTECH

E1 Vulnerability

SARA conducted pulsed current injection tests on a typical substation battery charger and found damage occurred at the highest stress associated with a conducted E1 pulse and temporary upsets associated with weaker pulses.[17] Potential for damage exists, given the length of unshielded cable connected to the battery charger and UPS and reliance on low-voltage electronics.

E3 and GMD Vulnerabilities

Battery chargers and UPS will see harmonic distortion from grid power during EMP events. While SARA did not test battery chargers and UPS in E3 environments, SARA predicts the design margin of typical devices installed in substations is sufficient to withstand an E3 pulse.[17] An NRC assessment of UPS in nuclear generating stations similarly found UPS to be "nearly immune" to GMD-induced harmonic

distortion.[18] Nonetheless, some evidence suggests vulnerabilities may exist for UPS in other applications. Testing at Idaho National Laboratory indicates UPS is vulnerable to harmonics caused by GIC within transformers. For example, Central Maine Power reported customer complaints due to UPS malfunctions during moderate solar storms.

Station Auxiliary Power Sources

Station auxiliary power sources feed uninterruptible power supplies that, in turn, power substation relays, SCADA units, and other low-voltage devices. The two principal sources of station auxiliary power are dedicated station power transformers and tertiary windings in step-down transformers. Some studies have found tertiary windings to be vulnerable to overheating from the E3 pulse and GMD. The vulnerability of station auxiliary power sources is an area appropriate for future study.

Backup Generators

Roughly 5% of substations have dedicated backup generators in addition to the battery and UPS system. These generators maintain station power in the event of an outage lasting longer than the battery charge. Substations without dedicated backup generators can also be restored by mobile generators.

Figure 35: Backup Diesel Generator. Backup diesel generators can provide emergency substation power for circuit breakers, relays, and other control equipment. However, without specific design for EMP protection, generators can be vulnerable to the E1 pulse. Note the ventilation grates on the front and side of this metal enclosure that prevent the enclosure from providing Faraday cage shielding. Photo Credit: Wikimedia Commons/Dwight Burdette.

E1 Vulnerability

Because of the common use of digital controls, backup generators can be vulnerable to the E1 component of HEMP. Diesel generators were damaged during the Soviet HEMP tests. Soviet scientists evaluating test results judged the damage resulted from the E1 portion of the pulse.[5] Subsequent Russian experiments confirmed vulnerability of mobile diesel generators to HEMP.[22] This would be expected from the exposed cabling on generators conducting the pulse towards onboard, low-voltage electronics.

Generators connected to the substation UPS are expected to be more vulnerable than disconnected generators, because the power cables to the UPS will conduct the E1 pulse into the generators.

E3 and GMD Vulnerabilities

Backup generators are not directly connected to long lines that would conduct the slower E3 or GMD pulses and are, therefore, not vulnerable.

Distribution Systems

The electric distribution system is a radial network of distribution lines and transformers used to transmit electric power from the transmission system to the end consumer.

The scope of our study is protecting the bulk power system, which does not include distribution assets. This scope was selected because it is considered the highest priority from a cost-benefit perspective and the diversity of the distribution and load assets that would need to be considered to assess vulnerability.

However, the E1 vulnerability of distribution systems and load has important implications for protection of the bulk power system. Because most generation plants cannot operate without external load, some load from the distribution system will be needed to blackstart the grid. The loss of load can facilitate system collapse and complicate efforts at system restoration.

Distribution systems are expected to experience E1 vulnerabilities analogous to those found in transmission systems. Insulators and transformers, designed to work at lower voltages, are expected to be more vulnerable to E1 than transformers supporting high-voltage transmission systems. The Congressional EMP commission estimated near instantaneous loss of more than 10% of load following an EMP. Metatech and the Congressional EMP Commission both list failures of insulators on distribution lines due to E1 induced flashovers as a key vulnerability warranting further study.[4]

The Congressional EMP Commission also assessed expected damage to the distribution system as "less dramatic" than that to the transmission system following an EMP, likely due to lower levels of digitization in the distribution system. Additionally, distribution systems and their loads are expected to be less vulnerable to E3 due to shorter transmission line lengths.

Communications and Control

In the United States, a network of regional control centers manages the generation and transmission of electricity. Utilities use control centers and communications to monitor and forecast grid conditions and send operating instructions to other utilities or directly to grid assets.

Control Centers

Control centers rely on computer equipment and are similar in construction to large data centers. Their components—workstation computers, servers, routers, and other IT equipment with unshielded microprocessors—are expected to be highly vulnerable to the E1 component of EMP. Ethernet ports, in

particular, are vulnerable to low levels of E1.[4] Equipment within control centers is typically powered by uninterruptible power supplies, which may vulnerable to transformer harmonics caused by the E3 pulse and GMD.

Figure 36: Reliability Coordinator Control Room. This reliability coordinator control room contains numerous monitors and large screen displays. The digital circuitry necessary to operate this equipment can be vulnerable to the E1 pulse. E3/GMD can cause harmonic effects misoperation of UPS if the control facility is unprotected. Photo Credit: Wikimedia Commons/Dpysh w.

Communications

Electric grid operators make extensive use of diverse communications technologies, including dedicated fiber optics, microwave, wireless cellular, and copper-conductor landlines. While much of electric grid communications is owned and operated by electric utilities, use of leased lines and the public internet has increased in recent years.

Nearly all electric grid substations are unmanned and remotely controlled, necessitating long-haul communications between control centers and the substations. While most electric generation plants are manned, their dispatch is done remotely, necessitating communication between control centers and the plants. Automatic generation control (AGC), the technology used to fine-balance generation and load, also requires communications between control centers and generation plants. This electric grid communication is performed using equipment not designed for EMP resilience and, therefore, possibly susceptible to temporary upset or permanent damage from the E1 pulse and GMD. Utilities use leased lines and the public Internet for many grid control activities. The cost of protecting electric grid

communications against EMP is covered in our companion report, "Protecting U.S. Electric Grid Communications from Electromagnetic Pulse."[26]

5. EMP Protection Strategies and Unit Costs

We developed EMP protection strategies based on the vulnerabilities addressed above and present them in two categories: hardening strategies and sparing strategies. We then used these strategies to develop per-unit estimates for EMP protection.

Hardening strategies directly protect equipment by blocking the EMP or designing equipment to withstand the EMP environment while operating. Within the DoD, the primary EMP hardening strategy is to block EMP by enclosing the equipment or facility within an electromagnetic barrier.[27] Given the scale of electric power transmission and generation infrastructure, applying this strategy directly to most grid assets would be cost prohibitive. Therefore, in most cases where hardening is applied, protection must occur at the subsystem or box level. Since DoD experience is not always directly applicable to grid protection and since little experience exists for EMP hardening of high-voltage grid components, our hardening cost estimations are necessarily approximate.

Sparing strategies increase grid resilience by facilitating timely restoration of systems damaged by EMP. These strategies can be cost-effective for grid components expected to have a low failure rate during an EMP event and for grid components with a high degree of redundancy, because not every component will incur a protection cost.

We estimated the cost of implementing spares by referencing RSMeans™ electric equipment cost data.[28] We supplemented RSMeans™ by using other industry cost estimates, where appropriate. In estimating the cost of implementing a sparing strategy, a source of uncertainty is the appropriate number of spares to stock. Since few grid components have been widely tested to failure against EMP environments, expected failure rates are largely unknown. Increased equipment testing will improve estimation of the requisite spares to ensure grid resilience from an EMP event and could lead to lower protection costs.

Transmission System Substations

We implement the following protection strategies for substations in our cost model:

- To protect against E3 and GMD, install neutral ground blockers on large power transformers at substations operating at 345kV or above
- To protect against E3 and GMD, maintain offline, on-site, spare circuit breakers at substations operating at 100kV or above
- To protect against E1, install electromagnetically shielded control houses with protected points of entry at substations operating at 100kV or above
- To aid in grid restoration after EMP events, install stationary backup generators at critical substations operating at 230kV or above

Our cost model does not include protections for these substation elements:

- Voltage support devices such as capacitors, reactors, and static VAR compensators and their digital controls
- Digital monitoring devices exposed to the E1 pulse in the open air of the substation, including digital instrument transformers and power transformer health monitors
- Cooling systems for power transformers
- Physical security systems such as closed-circuit television (CCTV)
- SCADA terminals outside the substation control house
- Any other digital devices in the open air of the substation that lack inherent E1 resilience or sufficient spares stocked on site

Comprehensive EMP protection for substations will require an inventory of digital devices exposed to the E1 pulse and evaluation of their vulnerability. Our cost estimate does include $1 million per substation for engineering study of the substation's EMP vulnerabilities.

Costs for EMP hardening of communications used in transmission systems are covered in our companion report, "Protecting U.S. Electric Grid Communications from Electromagnetic Pulse."[26]

Neutral Ground Blocking Devices

Neutral ground blocking devices are capacitor-based devices able to block GIC from E3/GMD, directly protecting power transformers. In addition to protecting the transformer, installation of a neutral ground blocking devices, by interrupting GIC, prevents the formation of harmonics due to transformer half-cycle saturation.

An alternative protection strategy could be to design and install new transformers with greater tolerance for overheating.[11] [29] However, greater thermal tolerance would not prevent the formation of harmful harmonics. A protection strategy incorporating neutral ground blockers would protect other equipment vulnerable to harmonics and reduce instances of relay misoperation from E3 and GMD. Installation of neutral ground blockers at some but not all substations, however, may increase GIC in transformers without blocking devices; network-specific modeling will be required to quantify this risk.

Figure 37: Neutral Ground Blocking Device. Utility workers examine a neutral ground blocking device installed to left of step-down transformer in an operational transmission system. This device blocks harmful GIC and prevents transformer oversaturation, overheating, and harmonic production. Installation of these devices at key grid nodes could protect against both E3 and GMD. Photo credit: Emprimus

Direct protection for large transformers is important due to the difficulty and cost of replacing them. Large power transformers have long replacement lead times—two years under normal circumstances—and most are uniquely designed, complicating implementation of a sparing strategy. Furthermore, the size and weight of large power transformers make transportation and installation difficult, often necessitating shipment by specialized rail cars and tractor trailers.

DOE has, however, awarded several contracts to develop lighter, modular transformer designs that could be used to more effectively implement a sparing strategy.[16] These transformers could be an important supplement to neutral ground blockers or reduce the need for neutral ground blockers for less critical transformers.

At the time of this report, only a single neutral ground blocking device had been installed within the U.S. electric grid.[30] Equipment costs were approximately $500,000. A recent DOE pilot study of the device found installation costs to be an additional $470,000.[31] Representatives from the company that designed the device stated this cost reflects the additional time to install a first-of-a-kind device and estimated that Nth-of-a-kind installations could cost as little as $25,000.

Our cost model applies a neutral ground blocking device to each transformer operating at the transmission level at or above voltage of 345 kV. We used the quoted equipment cost of $500,000 and $100,000 for installation as a conservative estimate of an Nth-of-a-kind installation.

Circuit Breaker Spares

Circuit breakers are well-suited to a sparing strategy for two reasons. First, circuit breakers may experience a low failure rate during a HEMP or extreme GMD event if they are not operated. Second, unlike transformers, circuit breakers are more standardized and can be used across substations if the breaker is of a sufficient voltage rating.

Additionally, circuit breakers in the bulk power system already have substantial redundancy. Most extra high-voltage substations, which comprise the backbone of the bulk power system, are configured in a 'breaker and a half' configuration. While this redundancy reduces the need for additional offline spares, the lack of data on expected circuit breaker failure rates during HEMP and GMD events complicates development of an adequate sparing strategy. More engineering study is needed.

Our cost model provides for an offline, spare circuit breaker rated for the substation's highest voltage for each substation operating at the transmission level. We used cost data adapted from RSMeans to estimate the breaker cost for several voltage classes. [32] Since the breaker is offline, no installation cost is added.

Table 1: Circuit Breaker Cost Estimates

Min Voltage (kV)	Max Voltage (kV)	Cost
500	1,000	$ 1,175,000
345	499	$ 780,000
235	344	$ 500,000
100	234	$ 310,000

Table 1 shows how the cost of spare circuit breakers would vary by maximum operating voltage. Circuit breaker costs increase with higher voltage class.

Shielded Control Houses

Substation control houses contain relays and SCADA components as well as the uninterruptible power supply from which they draw power. Given the small footprint of these buildings and the number of potentially vulnerable devices they contain, creating a hardened enclosure is expected to be the most cost-effective protection strategy.

At its substations, American Electric Power (AEP) has begun installing modular control houses with electromagnetic shielding. AEP has found these modular control houses, including electromagnetic shielding, are less expensive than their previous, unshielded control houses due to the economies of scale from mass production of the structures. AEP reports these structures cost $500,000 to procure.

Figure 38: Shielded Control Enclosure. This modular shielded enclosure can be used at grid substations to protect relays, SCADA, and communications equipment. Photo credit: ARMAG Corporation

Our cost model assumes a modular, hardened control house at each substation operating at the transmission level, 100 kV or above. Based on information from AEP and discussions with other vendors, we estimate the cost of an installed, EMP-hardened, substation control house at $1 million, twice the procurement cost.

Backup Generators

During a blackout, substations do not receive grid power to run the relays, SCADA, breakers, and switches necessary to operate and repower the substation. Substations, instead, rely on backup power sources to provide auxiliary power to the station until the grid is restored. Typically, backup power is provided by batteries with approximately eight hours of life, though this can be lengthened by reducing power consumption. In approximately 5% of transmission substations, batteries are supplemented by on-site backup generators.

Figure 39: Backup Generator in Shielded Enclosure. This modular shielded enclosure is used to EMP protect a backup diesel generator manufactured by Caterpillar. A protection strategy for shielded enclosures may be more cost effective than protecting individual components of the generator, such as engine controls. Photo credit: ARMAG Corporation

In the event of an EMP, GMD, or any blackout resulting from widespread damage to the bulk power system, restoration times may exceed the eight-hour life of substation batteries. To ensure control of these stations remains viable beyond this timeframe, additional backup generation capacity coupled with on-site fuel storage could be added to key substations. Such online generation capacity would, itself, require EMP protection, which could be achieved by housing the generator in an electromagnetically shielded container.

An alternative strategy would be to use fleets of offline mobile generators. Since mobile generators are normally offline, less EMP protection is required. A single unit might serve multiple substations sequentially. This strategy of using an offline mobile generator fleet compared to hardened, onsite generators could be more cost effective. However, ubiquitous EMP effects across wide regions and resulting logistics problems could render off-site equipment strategies ineffective.

Our cost model assumes installation of EMP-hardened backup generators at substations at or above 230kV. We assume the cost of a hardened generator and its fuel storage to be $100,000.

Engineering Studies

Site-specific engineering studies are needed to implement the prescribed substation protections and evaluate other EMP vulnerabilities. We estimate a rough order of magnitude cost of these studies at $1 million per substation, where protections are installed.

Substation Protection Methodology

Table 2: Example of Substation Protection Methodology

Substation Name	Item	Protection Basis	Unit Cost ($M)	Estimated Quantity	Cost ($M)
	Backup Generator (230+ kV)	New Equipment	$0.10M	1	$0.10M
	Circuit Breaker (345-499 kV)	Spare	$0.78M	1	$0.78M
Substation 1	Control House	New Equipment	$1.00M	1	$1.00M
	Neutral Ground Blocker (345+ kV)	New Equipment	$0.60M	2	$1.20M
	Engineering Study	Overhead	$1.00M	1	$1.00M
Total					**$4.08M**

Table 2 summarizes our protection cost estimation methodology for an example substation operating between 345-499 kV. Elements of substation protection are a spare circuit breaker, EMP-protected control house, backup generator for substations operating at 230 kV and above, and neutral ground blockers for substations operating at 345 kV and above. Different voltage circuit breakers are implemented depending on the substation's operating voltage (see Table 1).

Control Centers

Our proposed protection strategy for operations and control centers is to retrofit existing facilities with an electromagnetic shield with protected points of entry at all electrical and aperture penetrations (doors, pipes, vents, etc.). Our model applies EMP protection to all generating station operators responsible for generation that receives EMP protection, all transmission operators, and all reliability coordinators.

Significant experience exists in hardening operations centers against EMP. DoD EMP protection techniques and cost figures can be applied to electric grid control rooms and communications systems, because they are analogous to DoD operations centers and their communications. Additionally, two utilities recently completed new control centers with integrated EMP protection. CenterPoint Energy, a Houston-based transmission owner/operator, constructed a new control center at a total cost of $170 million of which $8M was directly attributed to EMP protection, less than 5% of total cost.[33] Dominion Energy's new EMP-hardened control center was built for $80 million.[34] [35]

Michael Caruso, an EMP protection consultant, provided congressional testimony on the cost of constructing operations and control facilities with EMP hardening based on his experience in the industry and with ETS-Lindgren, a company that implements EMP hardening for both the DoD and commercial customers. To retrofit a two-story, control center with 44,000 square feet of EMP hardened space, Caruso estimated $26 million total project cost or $590/ft^2.[36] Our model assumes Caruso's estimate of $590/ft^2 for control room retrofit EMP protection.

We classify control centers into three categories based on space requirements. Small control rooms require 2,400 ft^2 of protected space, medium centers 6,000 ft^2, and large centers 20,000 ft^2. Control centers are classified based on the entity's NERC designation and the size of assets for which the entity

is responsible. Size is assigned based on the following rules:

Large:
- Transmission operators with peak load of 10 GW or more
- Generation dispatch centers with capacity of 10 GW or more
- All entities that are both reliability coordinators and transmission operators

Medium:
- Transmission operators with peak load less than 10 GW but at least 5 GW
- Generation dispatch centers with capacity less than 10 GW but at least 5 GW
- Reliability coordinators that are not transmission operators

Small:
- Transmission operators with less than 5 GW of peak load
- Generation dispatch centers with less than 5 GW of capacity

Very small generation dispatch centers responsible for less than 100MW of dispatchable capacity are not included in the cost estimate.

Table 3: Examples of Control Room Protection Methodology

Utility Name	Role	Peak Load/ Capacity (MW)	Estimated Protected Area (ft²)	Cost ($/ft²)	Cost ($M)
Control Room 1	Transmission	7,500	6,000	$590.00	$3.54M
Control Room 2	General Dispatch	1,200	2,400	$590.00	$1.42M
Control Room 3	Reliability Coordinator & Transmission	-	20,000	$590.00	$11.80M

Table 3 summarizes our control room protection strategy and cost estimation methodology for three types of control rooms.

These examples of control rooms have the following characteristics:

- Control Room 1 is a transmission operator with 7,500 MW of peak load. It is classified as a medium control room requiring 6,000 ft² of protected space, costing $590/ ft²
- Control Room 2 is a generation dispatcher responsible for dispatching 1,200 MW of capacity and is classified as a small control room
- Control Room 3 is designated as both a reliability coordinator and transmission operator. It is classified as a large control room based solely on this designation

Generation Plants

To date, no large electrical generation plant has been hardened against EMP. Our review of power plant vulnerabilities finds electrical control systems to be E1 vulnerable, GSU transformers to be vulnerable to E3 and GMD, and generators to be vulnerable to E3/GMD indirectly via saturation-induced harmonics. GSU transformer and generator vulnerability to E1 has yet to be determined via test.

Our current cost model uses a rough estimate of the cost to retrofit existing power plants for EMP protection, based on the current cost of the asset's electrical and control systems and the cost of a neutral ground blocker. While crudely approximate, this method is necessitated by the diversity of power plant designs and lack of experience in protecting generation plants against EMP.

We adapt data on the costs of power plant electrical, instrumentation, and control from EIA's Capital Cost Estimates for Utility Scale Electricity Generating Plants, supplemented by a 2009 EPA-sponsored study on the performance and capital cost of subcritical coal power plants.[37] [38] [39] Estimates for power plant electrical, instrumentation, and control costs scale with the capacity of the plant and are subdivided by the type of plant. These costs include, "electrical transformers, switchgear, distributed control systems and other electrical commodities." As a conservative, order of magnitude estimate, we assume the cost of retroactively adding E1 protection to the plant's vulnerable electronics to be equal to the unhardened electrical, instrumentation, and control cost.

We make a small correction for the inclusion of the GSU transformer in EIA's electrical, instrumentation, and control cost estimate. We consider the cost protecting the GSU separately and explicitly as the equipment and installation cost of a neutral ground blocker. To separately account for this protection strategy, we estimate the cost of GSU transformers for a power plant to be $10,000/MVA. We then convert a plant's rated nameplate capacity in MW to MVA via its power factor (assuming a power factor of 0.85 if power factor data is unavailable). The cost of GSU transformers is subtracted from the electrical, instrumentation, and control costs. We added equipment and installation costs for a single neutral ground blocker for each generator (costs of $500,000 and $100,000 respectively).

Table 4: Power Plant Electrical, Instrumentation & Control Costs

Fuel	Type	Capital Cost ($/kW)	Electrical, Instrumentation & Controls Cost ($/kW)	Electrical, Instrumentation & Controls Cost (%)
Coal	Subcritical	$3,555	$213	6.0%
Coal	Supercritical	$3,246	$203	6.3%
Coal	UltraSupercritical	$3,636	$218	6.0%
Coal	IGCC	$4,400	$412	9.4%
Hydro	Conventional	$2,936	$141	4.8%
Hydro	Pumped Storage	$5,288	$256	4.8%
Gas	Steam Turbine	$978	$141	14.4%
Gas	Combustion Turbine	$917	$121	13.2%
Gas	Combined Cycle	$978	$141	14.4%
Gas	Internal Combustion	$1,342	$127	9.5%
Geothermal	Binary	$4,362	$367	8.4%
Geothermal	Dual Flash	$6,243	$359	5.8%
Nuclear	All	$5,945	$314	5.3%
Wind	Onshore	$1,877	$154	8.2%
Wind	Offshore	$6,230	$386	6.2%
Solar	Small (20 MW)	$2,671	$450	16.8%
Solar	Large (150 MW)	$2,534	$359	14.2%
Biomass	All	$4,985	$458	9.2%
Oil	All	$917	$121	13.2%

Table 4 shows how capital cost and electrical system cost vary by generating station technology. Because we assume EMP protection costs to be approximately equal to the electrical, instrumentation, and control system cost, plant technology is a significant cost driver. Hydroelectric plants, with their simple control systems, have lower EMP protection costs (as a percentage of plant capital cost) than modern, gas-fired plants with complex, digital control systems.

Table 5: Example of Generation Protection Methodology

Generator Name	Technology	Capacity (MW)	Capacity (MVA)	Power Factor	Cost Driver	Unit Cost	Quantity	Cost ($M)
					Electrical, Instrumentation & Controls Cost ($/MW)	$314,000	1000	$314.00M
Generator 1	Nuclear - Dual Unit	1000	1176	0.85	Generator Step-up Transformer ($/MVA)	$10,000	1176	($11.76M)
					Neutral Ground Blocker ($/ea.)	$600,000	1	$0.60M
Total								**$302.84M**

Table 5 summarizes our generating station protection strategy and cost estimation methodology. Generator 1 is a 1,000 MW nuclear generator located at a two-unit facility. The cost of electrical, instrumentation, and controls is estimated to be $314,000/MW or $314 million for the entire generating station. The cost of the GSU transformer is estimated to be $10,000/MVA. With an assumed power factor of 0.85, this totals $11.76 million, which is subtracted from the cost of electrical, instrumentation, and controls. The cost of a neutral ground blocker ($600,000 installed) is added to separately account for GSU protection. The total EMP protection cost for the example generating station is estimated to be $303 million.

6. EMP Protection Testing

Rigorous testing of EMP protection for the bulk power system will be challenging as it is impossible to test HEMP protection on a system-wide basis. (Russia is the only nation that has conducted a HEMP test over a large regional electric grid; this atmospheric test was conducted over Kazakhstan in 1962.) Instead, individual components and isolated systems must be tested to validate survivability. Rigorous HEMP testing will be costly, although economies might be gained through certification programs for commonly used electric grid devices and designs.

Once prototype EMP-protection of a grid component or system is completed, testing will be necessary for both EMP hardness and protection failure rates. There is a stochastic aspect to EMP failures; sufficient tests will be required to establish failure probabilities. Even a small percentage of projected failures among critical components in a large system such as the U.S. electric grid could cause system-wide cascading collapse.

Testing some components under loaded conditions—for example, large power transformers—will be complicated by hesitancy to risk interrupted load for commercial grid customers. Fortunately, Idaho National Laboratory has a moderate-scale electric grid within its boundaries that can be used for loaded condition testing.

Individual electric grid components can be EMP tested using current injection. This technique works well when the primary risk is EMP pulses conducted into equipment from attached cabling and cords. For transformers subjected to the E3 pulse and GMD, DC currents can be injected to simulate GIC in transmission lines.
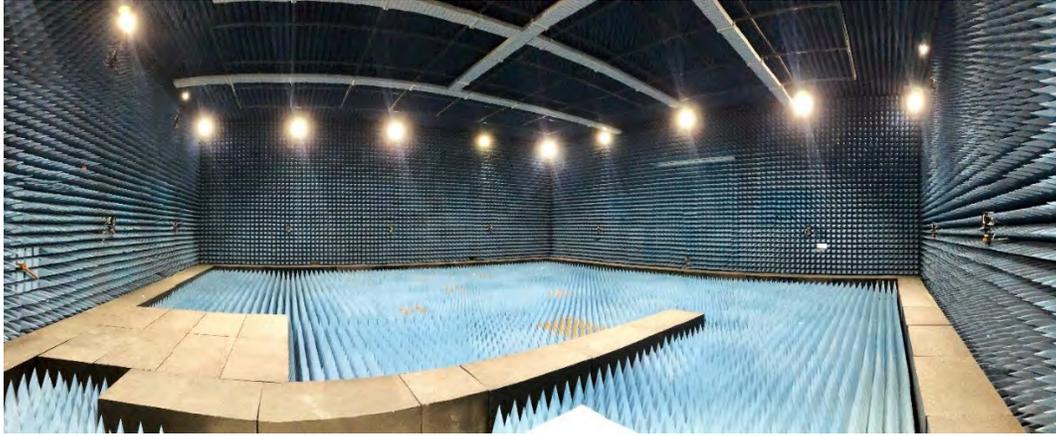
Figure 40: EMP Test Chamber. Anechoic EMP test chambers can be used to test equipment up to the size of an automobile or small truck. Photo credit: Global Resilience Institute at Northeastern University.

Small and moderately sized components can also be tested within an EMP chamber. Because such testing is already required for compliance with electromagnetic interference (EMI) standards, an established vendor base exists for such testing. The walls of EMP test chambers are typically lined with material to absorb electromagnetic radiation to make them anechoic (non-reflecting).

For devices protected by an enclosure, EMP can be generated outside (or inside) the enclosure and then the signal strength monitored inside (or outside) the enclosure. This technique is well-developed for testing enclosures used for DoD systems; the same techniques could be used for electric grid control centers and control houses at grid substations.
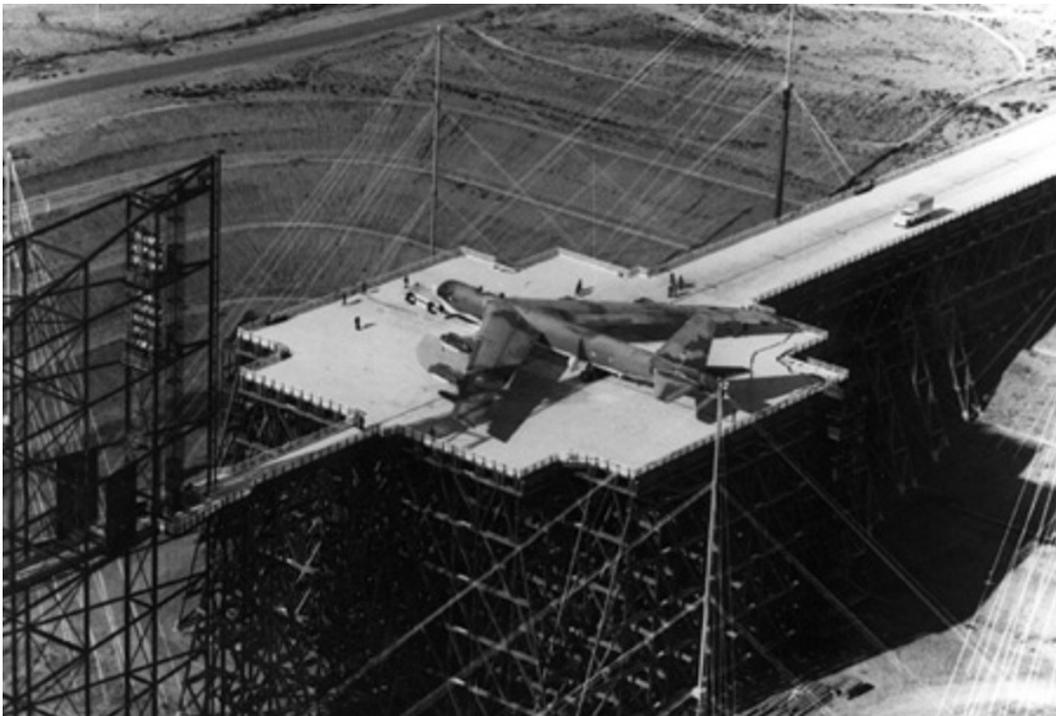
Figure 41: EMP Trestle. A Boeing B-52 strategic bomber being prepared for EMP testing at Atlas Trestle in 1982. Photo credit: U.S. Air Force

A testing approach for moderately sized systems is to use a "trestle"—a wooden support structure surrounded by EMP generators using capacitors, rapid-firing switches, and antennas. The U.S. Air Force used such a device from 1980 to 1991 under the Air Force Weapons Lab Transmission-Line Aircraft Simulator (ATLAS) program. Large military aircraft were placed within the trestle, then destructively tested. While the ATLAS program was shut down, knowledge gained was used to build the Z Pulsed Power Facility (Z Machine), the world's largest high-frequency electromagnetic wave generator located at Sandia National Laboratories. Small systems such as portable substations might be tested within EMP trestles.

7. Characterization of Bulk Power System Assets

In assessing the cost of protecting the U.S. electric grid against EMP and GMD threats, the Foundation for Resilient Societies constructed a database of bulk power system assets from publicly and commercially available sources. Resilient Societies' database of U.S. bulk power systems contains counts, key attributes, and locations of grid-connected electric generators, high-voltage lines and substations, and utility and reliability coordinator control centers. The database is implemented in Sequential Query Language (SQL). Data was compiled from the following sources:

Generation:

- EIA 860 – Data on generation units and power plants [40]

Transmission:

- HIFLD – Data on transmission lines and substations [41]
- S&P Platts – Data on substations
- FERC Form 1 – Data on substations [42]

Control Centers:

- NERC Registry Matrix – Data on transmission operators and reliability coordinators [43]
- EIA 860 – Data on generation operators including independent power producers [40]
- EIA 861 – Data on electric utility companies [44]

Jurisdictions:

- U.S. Census – State, county, statistical area, and congressional district boundaries
- NERC – ISO, NERC region, and Balancing Authority boundaries

When assets were reported by multiple sources, data was synthesized to create the most complete characterization of the assets and to avoid duplicate asset counts.

In total, our database characterizes over 32,000 substations above 100kV; 5,400 utilities and other entities with responsibility for the electric grid; and over 18,000 power plants comprising 1,156 GW of electrical generation capacity.

8. Estimated Cost of EMP Protection

We aggregated EMP protection cost estimates by applying each per-unit protection strategy identified in Section 6 to the applicable number of assets identified in the bulk power system database described in Section 8 and then summing the costs. We present here a breakdown of the national and state-level cost estimates.

Using our first-order cost model, we estimate the "overnight cost"[‡] of EMP protecting critical elements of U.S. bulk electric system to be on the order of $255 billion. This cost estimate includes protection for transmission system assets connected at 100kV and above; for dispatchable generators with at least 100MW of capacity; and for control rooms for transmission operators, generation dispatch, and reliability coordinators. Addition of EMP protection for voltage regulation devices such as SVCs could substantially increase protection costs, as could addition of vulnerable digital devices in the open air of substations. Alternatively, technological innovations and scale economies achieved over thousands of grid facilities could reduce EMP protection costs. Additional engineering and economic study would be required to refine these cost estimates for EMP protection.

It is important to note, cost estimates presented here consider only the cost of bulk power system protection and not the cost to protect the downstream assets that receive power (i.e., distribution and load).

Figure 42: Estimated U.S EMP Protection Costs by Grid Facility Type
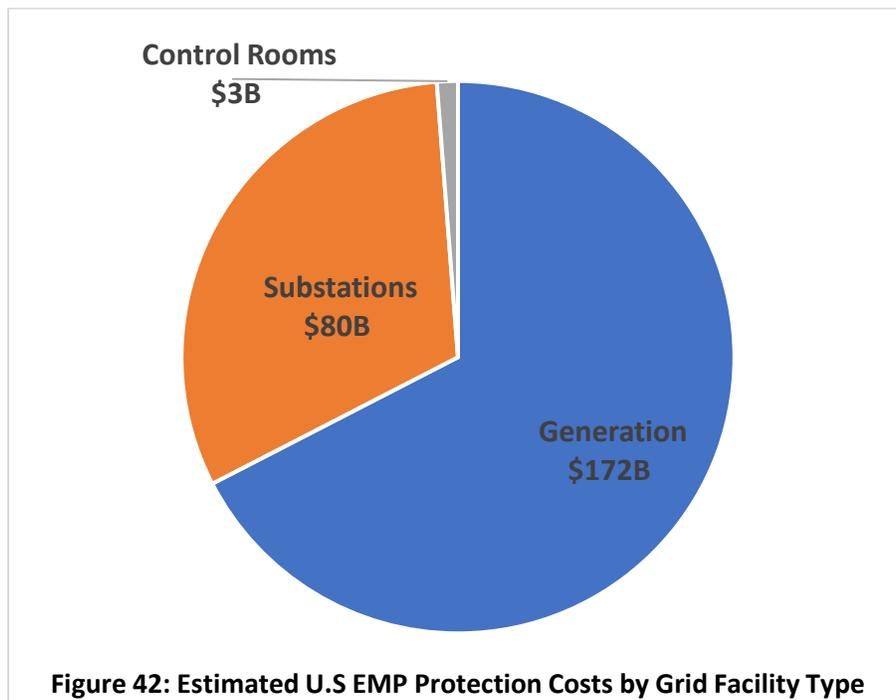
We estimate over two-thirds of this EMP protection cost is attributable to generating station protection, nearly one-third to substations, and only 1% to control room protection (Figure 42).

[‡] In the electric utility industry, "overnight cost" is the theoretical cost of building a facility or making an improvement in just one night. Obviously, this schedule would not be practical for EMP protection. Instead, we propose implementation of EMP protection over a full decade.

Our cost estimate for hardening control rooms is based on square footage provided in Michael Caruso's congressional testimony based on his experience with ETS Lindgren.[36] While we believe this is the best available data on the subject, we find our estimates for control room protection are lower than expected from costs realized by the two hardened control centers built at CenterPoint and Dominion Power. While control room costs may increase in subsequent iterations of EMP protection cost models, even an order of magnitude increase in control room cost would increase our overall protection estimate by only 10%.

Figure 43: Estimated U.S. EMP Protection Costs by Grid Threat
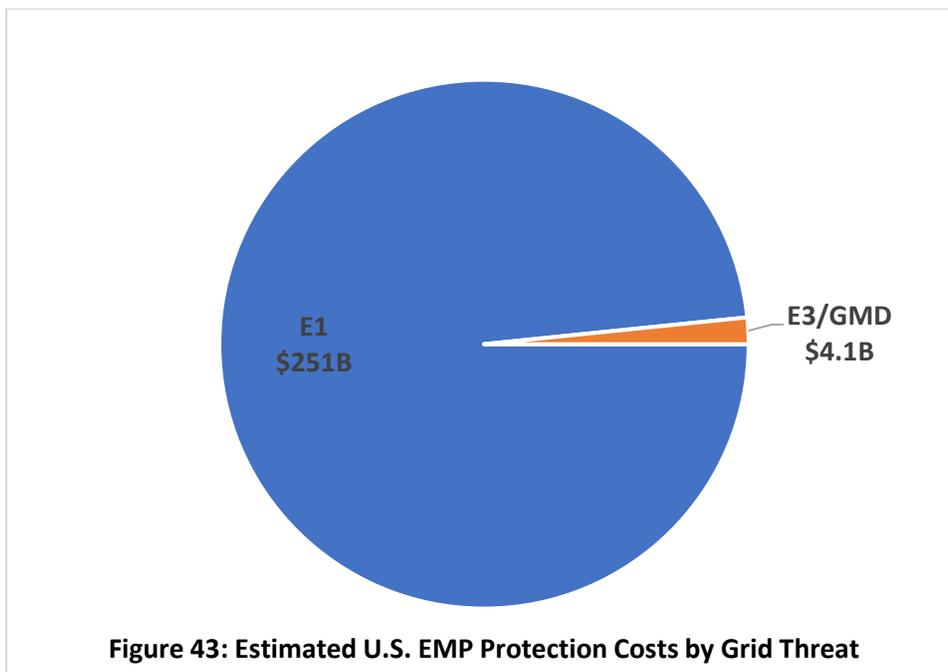
We find the cost of protection against the E1 pulse is significantly greater than the cost of protecting against E3 and GMD. We allocate the cost of neutral ground blocking devices at substations and generating station to the E3/GMD threat with all other protections allocated to E1. Under this classification, E3/GMD constitutes less than 2% of total protection costs (Figure 43).

E3 and GMD protection should be prioritized because they threaten large power transformers—expensive assets with long lead times—and, GMD is a natural phenomenon that cannot be deterred. Lloyd's of London (Lloyd's) estimates the economic cost of a Carrington-class solar storm on the North American electric grid at between $0.6 and $2.6 trillion based on the value of lost load (VOLL).[8] By this conservative assessment, the value at risk could be over 500 times the cost of E3/GMD hardening.

Breakdown of EMP Protection Costs

Because our first-order methodology estimates the cost of protecting most large assets within the U.S. bulk power system, our estimate of $255 billion could be higher than for a prioritized program of EMP protection. A credible deterrent against nuclear HEMP could be established by protecting grid assets sufficient to ensure basic societal functioning.

Table 6: Breakdown of EMP Protection Costs by Substation Operating Voltage

Substation Operating Voltage	Number of Substations	Number of Protected Substations	Protection Cost	Percent Protected	Percent of Protection Costs
500 kV+	930	930	$4,162M	100%	5%
345-499 kV	1,785	1,785	$7,283M	100%	9%
230-344 kV	4,657	4,657	$11,224M	100%	14%
116-229 kV	13,253	13,253	$30,614M	100%	38%
100-115 kV	11,590	11,590	$26,773M	100%	33%
Total	**32,215**	**32,215**	**$80,056M**	**100%**	**100%**

Table 6 breaks down substation assets within the United States by maximum substation operating voltage. This analysis shows as the operating voltage of substations declines, their count and proportional costs of EMP protection rise. Protecting only the most critical substations—those operating at 230 kV and above— might save 71% of estimated costs to protect substations. If we were to take a more cautious approach and install Neutral Ground Blockers for any substation operating above 100kV, we would see the protection cost due to blockers increase by 44% to $115,456M. This may not be cost-effective but should be considered if blocker technology advancements reduce the protection cost.

Table 7: Breakdown of EMP Protection Costs by Generation Plant Capacity

Genration Plant Capacity	Total Capacity (MW)	Number of Units	Protected Capacity (MW)	Number of Protected Units	Percent Protected	Protection Cost	Percent of Protection Costs
1,000+ MW	90,543	75	90,543	75	100%	$25,459M	15%
500-999 MW	262,933	377	262,933	377	100%	$51,988M	30%
250-499 MW	177,532	531	168,829	501	95%	$27,687M	16%
100-249 MW	366,683	2,249	320,411	1,941	87%	$44,222M	26%
0-99 MW	259,014	14,843	172,603	3,931	67%	$22,834M	13%
Total	**1,156,705**	**18,075**	**1,015,319**	**6,825**	**88%**	**$172,190M**	**100%**

Table 7 breaks down generation plants by capacity. In this table, plants under 100MW, renewables, and hydro plants under 10MW are not considered, as it might not be cost effective to protect them. This analysis shows that a strategy of protecting only the largest generation plants could save substantial funds. Protecting the most critical generation plants—those with capacity of 500 MW or more—could save 55% of estimated costs to protect generators.

Table 8: Breakdown of EMP Protection Costs by Generator Technology

Generator Technology	Total Capacity (MW)	Number of Units	Protected Capacity (MW)	Percent Protected	Protection Cost	Percent of Protection Costs
Gas	504,036	5,716	480,745	95%	$60,041M	35%
Coal	304,846	968	301,146	99%	$60,198M	35%
Nuclear	103,865	99	103,865	100%	$31,511M	18%
Hydro	100,812	4,176	94,576	94%	$14,862M	9%
Wind	73,511	1,098	-	0%	$0M	0%
Oil	39,941	3,510	29,462	74%	$3,282M	2%
Solar	13,543	1,649	-	0%	$0M	0%
Biomass	12,317	662	3,756	30%	$1,678M	1%
Geothermal	3,834	197	1,769	46%	$618M	0%
Total	**1,156,705**	**18,075**	**1,015,319**	**88%**	**$172,190M**	**100%**

Table 8 breaks down generation plants and protection costs by technology. This analysis indicates a strategy of excluding certain technologies from protection is unlikely to produce substantial savings. Gas-fired, coal-fired, nuclear, and hydro plants account for the majority of generation capacity. Under our protection scheme, these plants also account for 97% of estimated protection costs.

Allocation Methodologies for Costs

We allocated EMP protections by political jurisdictions (states), by annual electricity billings within states, by annual electricity sales (consumption) with states, average annual electricity expenditure, and per capita (by population). In general, we find that allocating costs by state results in residents of states that export power shouldering a disproportionate share of EMP protections costs—because generating stations account for the two-thirds of estimated EMP protection costs.

Table 9: Estimated EMP Protection Costs by State and Facility Type

State	Generation	Substations	Control Rooms	Total
Alabama	$5,678M	$4,798M	$47M	$10,523M
Alaska	$204M	$120M	$36M	$361M
Arizona	$4,969M	$887M	$58M	$5,914M
Arkansas	$2,837M	$1,927M	$33M	$4,798M
California	$8,476M	$4,178M	$278M	$12,932M
Colorado	$2,161M	$1,351M	$67M	$3,580M
Connecticut	$1,450M	$616M	$48M	$2,114M
Delaware	$440M	$303M	$10M	$753M
District of Columbi	$0M	$31M	$5M	$35M
Florida	$9,807M	$4,002M	$146M	$13,955M
Georgia	$6,300M	$4,019M	$77M	$10,396M
Hawaii	$392M	$113M	$22M	$527M
Idaho	$482M	$888M	$19M	$1,389M
Illinois	$9,085M	$2,645M	$107M	$11,837M
Indiana	$4,880M	$1,706M	$63M	$6,649M
Iowa	$1,905M	$1,017M	$55M	$2,977M
Kansas	$1,859M	$1,002M	$46M	$2,907M
Kentucky	$4,116M	$997M	$34M	$5,146M
Louisiana	$4,288M	$1,931M	$51M	$6,269M
Maine	$508M	$484M	$19M	$1,011M
Maryland	$2,263M	$697M	$34M	$2,993M
Massachusetts	$2,106M	$1,119M	$102M	$3,327M
Michigan	$5,500M	$1,828M	$80M	$7,408M
Minnesota	$2,158M	$1,881M	$65M	$4,103M
Mississippi	$2,722M	$2,330M	$22M	$5,074M
Missouri	$3,925M	$1,655M	$77M	$5,658M

Table 9: Estimated EMP Protection Costs by State and Facility Type – Continued

State	Generation	Substations	Control Rooms	Total
Montana	$829M	$467M	$22M	$1,317M
Nebraska	$1,509M	$846M	$72M	$2,427M
Nevada	$1,464M	$718M	$36M	$2,218M
New Hampshire	$784M	$279M	$19M	$1,082M
New Jersey	$3,284M	$951M	$45M	$4,280M
New Mexico	$1,178M	$1,317M	$19M	$2,514M
New York	$6,105M	$2,402M	$121M	$8,629M
North Carolina	$5,683M	$2,367M	$116M	$8,166M
North Dakota	$1,009M	$471M	$22M	$1,501M
Ohio	$5,182M	$2,434M	$124M	$7,741M
Oklahoma	$3,262M	$1,436M	$66M	$4,764M
Oregon	$1,718M	$1,608M	$79M	$3,405M
Pennsylvania	$8,272M	$1,865M	$101M	$10,239M
Rhode Island	$248M	$185M	$10M	$443M
South Carolina	$4,959M	$1,482M	$24M	$6,465M
South Dakota	$448M	$412M	$27M	$887M
Tennessee	$4,229M	$1,970M	$43M	$6,242M
Texas	$16,418M	$7,868M	$360M	$24,647M
Utah	$1,394M	$592M	$24M	$2,010M
Vermont	$16M	$230M	$21M	$268M
Virginia	$4,549M	$1,925M	$52M	$6,526M
Washington	$4,010M	$2,524M	$70M	$6,604M
West Virginia	$2,790M	$1,380M	$10M	$4,180M
Wisconsin	$2,870M	$1,310M	$42M	$4,222M
Wyoming	$1,471M	$483M	$7M	$1,961M
Total	**$172,190M**	**$80,049M**	**$3,134M**	**$255,373M**

Table 9 shows the absolute cost of EMP protecting assets in each state. As expected, larger states have more electric grid assets and, therefore, greater estimated costs for EMP protection.

Table 10: Impact of EMP Protection on Electricity Rates

State	Annual Electricity Billings	Annualized EMP Protection Cost	Percent Increase in Electricity Cost
Alabama	$8,436M	$1,052M	12.5%
Alaska	$1,097M	$36M	3.3%
Arizona	$8,082M	$591M	7.3%
Arkansas	$3,753M	$480M	12.8%
California	$37,193M	$1,293M	3.5%
Colorado	$5,386M	$358M	6.6%
Connecticut	$3,609M	$211M	5.9%
Delaware	$1,168M	$75M	6.4%
District of Columbia	$990M	$4M	0.4%
Florida	$23,348M	$1,396M	6.0%
Georgia	$13,239M	$1,040M	7.9%
Hawaii	$2,254M	$53M	2.3%
Idaho	$1,864M	$139M	7.4%
Illinois	$10,754M	$1,184M	11.0%
Indiana	$9,557M	$665M	7.0%
Iowa	$4,142M	$298M	7.2%
Kansas	$4,282M	$291M	6.8%
Kentucky	$6,275M	$515M	8.2%
Louisiana	$6,811M	$627M	9.2%
Maine	$1,216M	$101M	8.3%
Maryland	$6,341M	$299M	4.7%
Massachusetts	$6,623M	$333M	5.0%
Michigan	$11,441M	$741M	6.5%
Minnesota	$6,623M	$410M	6.2%
Mississippi	$4,238M	$507M	12.0%
Missouri	$7,660M	$566M	7.4%

Table 10: Impact of EMP Protection on Electricity Rates – Continued

State	Annual Electricity Billings	Annualized EMP Protection Cost	Percent Increase in Electricity Cost
Montana	$1,230M	$132M	10.7%
Nebraska	$2,732M	$243M	8.9%
Nevada	$3,023M	$222M	7.3%
New Hampshire	$1,472M	$108M	7.4%
New Jersey	$8,677M	$428M	4.9%
New Mexico	$2,100M	$251M	12.0%
New York	$16,399M	$863M	5.3%
North Carolina	$12,301M	$817M	6.6%
North Dakota	$1,655M	$150M	9.1%
Ohio	$11,237M	$774M	6.9%
Oklahoma	$4,746M	$476M	10.0%
Oregon	$4,142M	$341M	8.2%
Pennsylvania	$12,416M	$1,024M	8.2%
Rhode Island	$998M	$44M	4.4%
South Carolina	$7,676M	$646M	8.4%
South Dakota	$1,192M	$89M	7.4%
Tennessee	$9,299M	$624M	6.7%
Texas	$33,584M	$2,465M	7.3%
Utah	$2,631M	$201M	7.6%
Vermont	$797M	$27M	3.4%
Virginia	$10,137M	$653M	6.4%
Washington	$6,793M	$660M	9.7%
West Virginia	$2,879M	$418M	14.5%
Wisconsin	$7,375M	$422M	5.7%
Wyoming	$1,355M	$196M	14.5%
Total	**$363,228M**	**$25,537M**	**7.5%**

Table 10 shows the annual cost of EMP protection if evenly divided across a 10-year program in comparison to the total annual cost of serving electricity in each state.[§] We estimate EMP protection of the entire bulk power system would increase the cost of serving electricity on average by 7.5% nationally if implemented over a 10-year period. If costs were allocated on a state-by-state basis, some states would experience a higher relative cost due to the make-up of their portfolio of power system infrastructure. States that are significant importers of electricity, such as California and Vermont, would see the lowest relative increase in costs at approximately 3%, since they rely on generation assets outside their borders. Conversely, Wyoming and West Virginia, the states with the greatest relative increase in costs at roughly 14%, are significant electricity exporters. As expected, Texas, with a self-sufficient grid largely isolated from the rest of the nation, experiences a relative increase in cost in line with the national average at roughly 7%.

[§] This analysis represents a first-order estimation. For simplicity, it is conducted in nominal dollars.

Table 11: Impact of EMP Protection on Volumetric Rates

State	Annual Electricity Sales (TWh)	Annualized EMP Protection Cost ($M)	Volumetric Increase in Electricity Cost ($/MWh)
Alabama	88.2	$1,052M	$11.93
Alaska	6.1	$36M	$5.89
Arizona	78.2	$591M	$7.56
Arkansas	46.2	$480M	$10.39
California	256.8	$1,293M	$5.04
Colorado	54.8	$358M	$6.53
Connecticut	28.9	$211M	$7.31
Delaware	11.3	$75M	$6.68
District of Columbia	11.4	$4M	$0.31
Florida	235.7	$1,396M	$5.92
Georgia	138.1	$1,040M	$7.53
Hawaii	9.4	$53M	$5.58
Idaho	23.1	$139M	$6.02
Illinois	141.1	$1,184M	$8.39
Indiana	103.7	$665M	$6.41
Iowa	48.4	$298M	$6.15
Kansas	40.8	$291M	$7.12
Kentucky	74.6	$515M	$6.90
Louisiana	91.5	$627M	$6.86
Maine	11.4	$101M	$8.83
Maryland	61.4	$299M	$4.88
Massachusetts	53.5	$333M	$6.22
Michigan	104.5	$741M	$7.09
Minnesota	66.5	$410M	$6.17
Mississippi	49.1	$507M	$10.34
Missouri	78.6	$566M	$7.20

Table 11: Impact of EMP Protection on Volumetric Rates – Continued

State	Annual Electricity Sales (TWh)	Annualized EMP Protection Cost ($M)	Volumetric Increase in Electricity Cost ($/MWh)
Montana	14.1	$132M	$9.34
Nebraska	30.2	$243M	$8.04
Nevada	36.1	$222M	$6.14
New Hampshire	10.9	$108M	$9.92
New Jersey	75.4	$428M	$5.68
New Mexico	23.0	$251M	$10.91
New York	147.8	$863M	$5.84
North Carolina	134.4	$817M	$6.08
North Dakota	18.5	$150M	$8.11
Ohio	150.6	$774M	$5.14
Oklahoma	61.5	$476M	$7.75
Oregon	47.3	$341M	$7.19
Pennsylvania	145.3	$1,024M	$7.05
Rhode Island	7.5	$44M	$5.88
South Carolina	79.6	$646M	$8.12
South Dakota	12.1	$89M	$7.32
Tennessee	100.8	$624M	$6.20
Texas	398.7	$2,465M	$6.18
Utah	30.2	$201M	$6.66
Vermont	5.5	$27M	$4.86
Virginia	112.3	$653M	$5.81
Washington	88.9	$660M	$7.43
West Virginia	32.1	$418M	$13.03
Wisconsin	69.7	$422M	$6.05
Wyoming	16.6	$196M	$11.85
Total	**3,762**	**$25,537M**	**$7.17**

Table 11 shows the impact on electricity costs on a per megawatt-hour basis if this annualized cost were allocated volumetrically to the rate base on a state-by-state basis. Under this allocation methodology, the per-megawatt hour price of electricity would increase on average by approximately $7.17 (0.72 cents per kilowatt-hour). This would correspond to a $73 increase in an annual electricity expenditure for the average residential ratepayer for the life of the program (see Table 12).

While volumetric allocation provides a useful sense of scale of the cost of an EMP protection program, allocating costs in proportion to electricity consumption would have a distortive effect on electricity consumption as not all loads would demand EMP-resilient service. Recovering costs through volumetric rates could become particularly distortive if sufficient EMP protected capacity were guaranteed only to serve critical public services. To mitigate this effect, EMP protection costs could be added as a fixed cost to ratepayer bills. Alternatively, EMP protection may best be viewed as a defense expenditure with costs socialized throughout the tax base.

Table 12: Impact of EMP Protection on Residential Ratepayers

State	Average Annual Electricity Expenditure ($)	Annualized Protection Cost Per Average Ratepayer ($)	Percent Increase for Average Ratepayer
Alabama	$1,393	$174	12.5%
Alaska	$1,270	$42	3.3%
Arizona	$1,277	$93	7.3%
Arkansas	$1,056	$135	12.8%
California	$951	$33	3.5%
Colorado	$819	$54	6.6%
Connecticut	$1,064	$62	5.9%
Delaware	$1,179	$76	6.4%
District of Columbia	$839	$3	0.4%
Florida	$1,335	$80	6.0%
Georgia	$1,309	$103	7.9%
Hawaii	$1,447	$34	2.3%
Idaho	$925	$69	7.4%
Illinois	$670	$74	11.0%
Indiana	$1,079	$75	7.0%
Iowa	$887	$64	7.2%
Kansas	$1,132	$77	6.8%
Kentucky	$1,133	$93	8.2%
Louisiana	$1,108	$102	9.2%
Maine	$697	$58	8.3%
Maryland	$1,234	$58	4.7%
Massachusetts	$890	$45	5.0%
Michigan	$878	$57	6.5%
Minnesota	$912	$57	6.2%
Mississippi	$1,248	$149	12.0%
Missouri	$1,217	$90	7.4%

Table 12: Impact of EMP Protection on Residential Ratepayers – Continued

State	Average Annual Electricity Expenditure ($)	Annualized Protection Cost Per Average Ratepayer ($)	Percent Increase for Average Ratepayer
Montana	$852	$91	10.7%
Nebraska	$1,056	$94	8.9%
Nevada	$928	$68	7.3%
New Hampshire	$978	$72	7.4%
New Jersey	$954	$47	4.9%
New Mexico	$691	$83	12.0%
New York	$792	$42	5.3%
North Carolina	$1,209	$80	6.6%
North Dakota	$1,122	$102	9.1%
Ohio	$798	$55	6.9%
Oklahoma	$1,013	$102	10.0%
Oregon	$952	$78	8.2%
Pennsylvania	$863	$71	8.2%
Rhode Island	$932	$41	4.4%
South Carolina	$1,336	$113	8.4%
South Dakota	$1,158	$86	7.4%
Tennessee	$1,371	$92	6.7%
Texas	$1,169	$86	7.3%
Utah	$784	$60	7.6%
Vermont	$953	$32	3.4%
Virginia	$1,213	$78	6.4%
Washington	$876	$85	9.7%
West Virginia	$1,187	$172	14.5%
Wisconsin	$867	$50	5.7%
Wyoming	$835	$121	14.5%
National Average	**$1,039**	**$73**	**7.0%**

Table 12 shows the impact on EMP protection on residential ratepayers if costs were to be allocated based on ratepayers' annual expenditures for electricity. Ratepayers in states such as West Virginia would be forced to pay much more in rate increases than ratepayers in states such as Maryland and Virginia. This is because West Virginia exports large amounts of power to Maryland and Virginia. Essentially, under this allocation scheme, ratepayers in West Virginia would pay to protect power for those in other states.

Table 13: EMP Protection Cost Per Capita

State	Population (M)	Annualized EMP Protection Cost	Annual Cost Per Capita ($)
Alabama	4.9M	$1,052M	$216.37
Alaska	0.7M	$36M	$48.64
Arizona	6.9M	$591M	$85.32
Arkansas	3.0M	$480M	$160.55
California	39.3M	$1,293M	$32.95
Colorado	5.5M	$358M	$64.61
Connecticut	3.6M	$211M	$59.12
Delaware	1.0M	$75M	$79.04
District of Columbia	0.7M	$4M	$5.21
Florida	20.6M	$1,396M	$67.70
Georgia	10.3M	$1,040M	$100.83
Hawaii	1.4M	$53M	$36.87
Idaho	1.7M	$139M	$82.50
Illinois	12.8M	$1,184M	$92.47
Indiana	6.6M	$665M	$100.24
Iowa	3.1M	$298M	$94.98
Kansas	2.9M	$291M	$100.01
Kentucky	4.4M	$515M	$115.99
Louisiana	4.7M	$627M	$133.91
Maine	1.3M	$101M	$75.96
Maryland	6.0M	$299M	$49.75
Massachusetts	6.8M	$333M	$48.84
Michigan	9.9M	$741M	$74.62
Minnesota	5.5M	$410M	$74.34
Mississippi	3.0M	$507M	$169.76
Missouri	6.1M	$566M	$92.85

Table 13: EMP Protection Cost Per Capita – Continued

State	Population (M)	Annualized EMP Protection Cost	Annual Cost Per Capita ($)
Montana	1.0M	$132M	$126.35
Nebraska	1.9M	$243M	$127.25
Nevada	2.9M	$222M	$75.43
New Hampshire	1.3M	$108M	$81.07
New Jersey	8.9M	$428M	$47.85
New Mexico	2.1M	$251M	$120.82
New York	19.7M	$863M	$43.70
North Carolina	10.1M	$817M	$80.48
North Dakota	0.8M	$150M	$198.10
Ohio	11.6M	$774M	$66.65
Oklahoma	3.9M	$476M	$121.43
Oregon	4.1M	$341M	$83.19
Pennsylvania	12.8M	$1,024M	$80.09
Rhode Island	1.1M	$44M	$41.90
South Carolina	5.0M	$646M	$130.31
South Dakota	0.9M	$89M	$102.54
Tennessee	6.7M	$624M	$93.85
Texas	27.9M	$2,465M	$88.46
Utah	3.1M	$201M	$65.87
Vermont	0.6M	$27M	$42.90
Virginia	8.4M	$653M	$77.58
Washington	7.3M	$660M	$90.62
West Virginia	1.8M	$418M	$228.26
Wisconsin	5.8M	$422M	$73.06
Wyoming	0.6M	$196M	$334.90
Total	**323.1M**	**$25,537M**	**$79.03**

Table 13 shows the cost to protect assets on state-by-state basis, over a 10-year program, with costs allocated per capita. If funded nationally, the program described above would cost approximately $79 per resident per year for the life of the program. Per capita costs would vary dramatically by state, because citizens in low-population states that export large amounts of power would pay a disproportionate share of costs for EMP protection.

9. Benefits of EMP Protection

The benefits of EMP protection are substantial, because an EMP attack or severe solar storm could cause a nation-wide, long-term collapse of the electric grid. Economic activity could also collapse, and millions of deaths could result. For example, Lloyd's estimates a Carrington-class solar storm over North America could cause between $0.6 and $2.6 trillion in economic losses, where the area of impact is limited mostly to the Atlantic coast area. Because the Lloyd's estimate is based on a metric commonly used to estimate losses from power disruptions of a few hours, a long-term outage could result in far greater losses.

If an EMP protection program is implemented, society would pay the costs of protection with 100 percent certainty, while the risk-adjusted benefits of EMP protection depend on the probability of an adverse outcome occurring. Because an EMP attack depends on human volition, its probability cannot be definitively estimated, but the deterrent effect of EMP protection should weigh heavily on the willingness of an adversary to risk an attack. Extreme geomagnetic disturbance, on the other hand, is a naturally occurring phenomenon. According to published research, the probability of a severe solar storm is approximately 10 percent per decade or over 50 percent during a full human lifetime.

The National Institute of Building Sciences has found that for every dollar invested in mitigation, six dollars are saved in restoration.[45] We have seen from the COVID-19 pandemic that the U.S. economy can be drastically affected by unmitigated vulnerabilities. An EMP event could have economic impact several times greater than the COVID-19 pandemic.

Protecting the U.S. electric grid is essential to preserve operation of lifeline sectors, which include water, wastewater services, food, healthcare, transportation, fuel, and emergency services. Paramount of these are water and wastewater services, both dependent on electric power. Lack of water and sanitation could directly lead to illness and epidemics. Electricity is also critical in manufacturing medical supplies, operating oil refineries and chemical plants, and preserving supply chains for other vital goods. All critical infrastructures are interdependent with the electric grid. Protecting the U.S. electric grid from EMP protects the nation.

10.   Conclusions

EMP protection for the U.S. bulk power system against HEMP from nuclear attack and GMD from solar storms would be a significant but affordable cost for American society. Using a transparent methodology, we assess the cost to be approximately $255 billion in total or $25.5 billion annually over ten years.

After a 10-year period to implement initial protection, maintenance costs would be incurred, as well as cost to protect equipment newly installed. As a first-order estimate, we propose that ongoing protection costs would be roughly equivalent to annual costs during the initial 10-year period.

These costs, while significant, would be a small percentage of the annual U.S. billings for electricity service, about 7% for the EIA billing data available for 2016. EMP protection would also be a small percentage of average per capita income within the United States; our estimated $79 per capita cost would be only 0.16% of mean per-capita income of $50,413 for 2018.

For comparison, our estimated annual cost of $25.5 billion would be about 5% of the annual U.S. defense budget and approximately 20% of capital expenditures for shareholder-owned electric utilities in 2018. The cost of EMP protection of the bulk power system, if implemented by regulation, would be within the

same order of magnitude of other costly federal regulations. For example, the EPA estimates the Mercury and Air Toxics Rule, the costliest of EPA rules, to have an annual cost of $9.6 billion.[46]

This EMP protection program would protect much of the bulk power system. We would expect a program prioritized to protect only the most critical transmission assets and a sufficient amount of generation capacity to meet critical loads to cost less. Notably, our cost estimates for EMP protection do not include electricity distribution systems. Future study is needed for distribution protection, because distribution elements are important to support critical public services and load for blackstart.

A comprehensive program to protect only against GMD or the E3 component of HEMP would cost substantially less—approximately 1.6% of the cost of more comprehensive EMP protection.

We expect the E3 pulse from a HEMP attack to cause greater damage than a severe solar storm, exacerbated by the damage from the E1 pulse to computer and telecommunications systems. If long-term disruption of electricity supply via an EMP attack or solar storm were to cause a one-year loss of 50% of GDP, this avoided cost would be on the order of $10 trillion. Using the EPA standard of $7.4 million per avoided death, if an EMP attack or severe solar storm were to cause a long-term blackout and the deaths of 10 million Americans, this avoided cost would be on the order of $74 trillion.

In summary, while the costs of EMP protection would certainly be substantial, they should be manageable in terms of overall expenditures for American society and far less than losses from an attack or severe solar storm. Protection of the bulk power system from HEMP, while not being comprehensive for all of the electric grid, would likely change the calculus of potential attackers and thereby increase nuclear deterrence. Protection against GMD would be a small portion of overall EMP protection costs—and would have high payoff in reducing risks from unavoidable solar storms. Because EMP is an existential threat to the United States—and therefore nearly unlimited in its potential for societal damage—a multi-year program of EMP protection should be both justified and affordable, especially if protections were prioritized and implemented over realistic timeframes. Improved understanding of the scope and costs of needed EMP protections is essential.

11.   Further Work

This report presents a framework for estimating the cost of EMP protection and an initial estimate of the cost to protect the bulk power system. With further research, improvements to the underlying methodology could and should be made. Within the transmission sector, these should include addition of protection strategies for voltage regulation devices and exposed digital devices in substations. The vulnerability of high-voltage transformers and circuit breakers has yet to be determined by test. Improvements to our cost estimation methodology for generating stations would have important impacts on the overall estimated cost of protection, given the lack of experience hardening such facilities and the high cost of protection. Better understanding of generation vulnerabilities will require engineering study and testing using EMP simulations; this work has been undertaken by the Defense Threat Reduction Agency. Refinements to the counts of equipment and facilities to be protected would significantly improve cost estimates, including prioritization strategies to maximize deterrence while minimizing costs.

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Exhibit J

"Protecting the grid from solar storms." Western Area Power Administration. April 2023.

CLOSED
Circuit

WESTERN AREA POWER ADMINISTRATION

APRIL 2023

Powering
WAPA
forward

1

12

CLOSED Circuit

Western Area Power Administration

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On the cover
Local police stand next to WAPA's Bell 407 helicopter following an in-flight incident with a paraglider, pictured on the left.
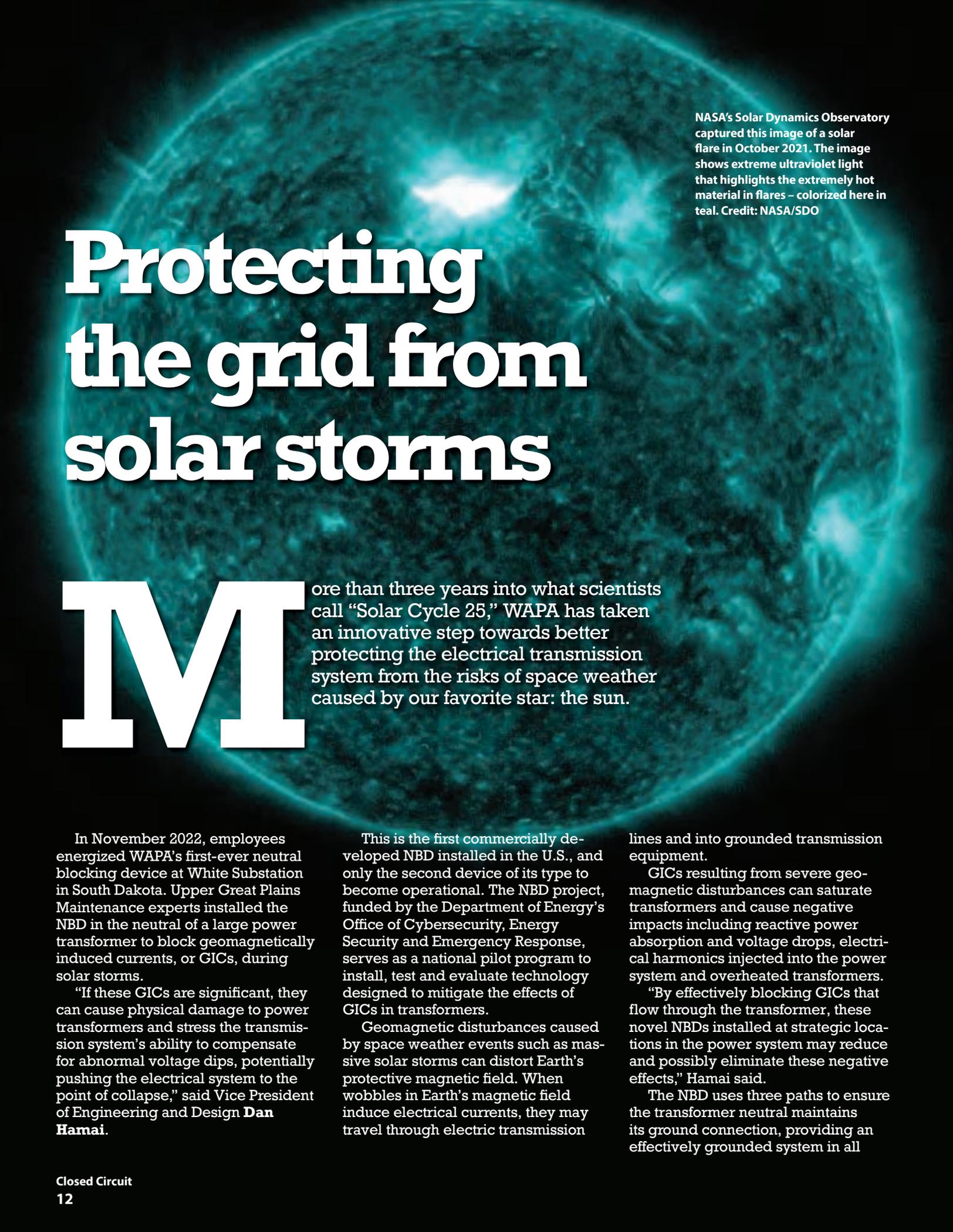
Protecting the grid from solar storms

More than three years into what scientists call "Solar Cycle 25," WAPA has taken an innovative step towards better protecting the electrical transmission system from the risks of space weather caused by our favorite star: the sun.

In November 2022, employees energized WAPA's first-ever neutral blocking device at White Substation in South Dakota. Upper Great Plains Maintenance experts installed the NBD in the neutral of a large power transformer to block geomagnetically induced currents, or GICs, during solar storms.

"If these GICs are significant, they can cause physical damage to power transformers and stress the transmission system's ability to compensate for abnormal voltage dips, potentially pushing the electrical system to the point of collapse," said Vice President of Engineering and Design **Dan Hamai**.

This is the first commercially developed NBD installed in the U.S., and only the second device of its type to become operational. The NBD project, funded by the Department of Energy's Office of Cybersecurity, Energy Security and Emergency Response, serves as a national pilot program to install, test and evaluate technology designed to mitigate the effects of GICs in transformers.

Geomagnetic disturbances caused by space weather events such as massive solar storms can distort Earth's protective magnetic field. When wobbles in Earth's magnetic field induce electrical currents, they may travel through electric transmission lines and into grounded transmission equipment.

GICs resulting from severe geomagnetic disturbances can saturate transformers and cause negative impacts including reactive power absorption and voltage drops, electrical harmonics injected into the power system and overheated transformers.

"By effectively blocking GICs that flow through the transformer, these novel NBDs installed at strategic locations in the power system may reduce and possibly eliminate these negative effects," Hamai said.

The NBD uses three paths to ensure the transformer neutral maintains its ground connection, providing an effectively grounded system in all

operating modes. These paths include a solidly grounded metallic path, a GIC-blocking path using a capacitor bank and an overvoltage protective path through a spark gap. When the GICs exceed a threshold setting, the NBD automatically opens the solidly grounded path, which directs all neutral current through a low impedance capacitor bank, effectively stopping the rogue current from sneaking onto the transmission system.

GICs are quasi-direct current, meaning they oscillate at frequencies so low that they act like direct current. Significant and sustained direct currents are rare on WAPA's alternating current transmission system and can cause detrimental effects when they flow. This explains why engineers use a capacitor in the blocking path. When faced with a GIC, the capacitor functions like an open circuit, blocking the GIC's flow.

"Ultimately, the benefit of this NBD design is to mitigate GMD effects on the transformer while maintaining a solid metallic grounded neutral under normal operating conditions, which is critical for equipment insulation and protective relay operation," said Transmission System Planning Manager **Chris Colson**.

Following a GIC mitigation pilot program report from the Electric Power Research Institute, WAPA experts performed two system studies to identify and analyze preferred locations for the NBD within the organization's transmission system. In the first study, UGP transmission planners performed a specialized GIC flow study to determine how solar storms of varying orientations and magnitude may cause GICs to develop on the transmission system.

They simulated placing NBDs at various crucial nodes, including large power transformers at substations positioned to serve numerous customers and sites.

The experts then analyzed the effectiveness of a GIC-blocking device in the field. They determined the transformer "KU1A" at White Substation would make the best Upper Great Plains candidate for NBD installation.

"White KU1A met our criteria as a substation transformer that connects to three or more adjacent substations

An Upper Great Plains Maintenance crew quickly installed WAPA's new neutral blocking device at the White Substation in September 2022.

with large bulk electric system transformers," said Colson.

"In other words, blocking GICs at this transformer allows any significant GICs developed on the long 345-kilovolt transmission lines terminating at White Substation to become somewhat reduced, but more importantly safely redistributed, finding paths to ground at adjacent substations," he said.

For the second study, an architectural engineering firm completed the "White Substation NBD Impact Study," which included transient switching analysis, harmonics analysis and insulation assessment to evaluate the potential impact of the NBD.

If any of WAPA's technical studies showed potential damage to the transformer or negative impacts to system reliability, WAPA would not move forward to purchase and install these GIC mitigation devices.

"We were pleased to find out that no negative impacts were identified, so WAPA moved into the design and NBD specification phase," Hamai said.

After finalizing the designs, WAPA procured the NBD from Emprimus LLC, which delivered it to White Substation in September 2022. A South Dakota-based Maintenance crew then installed the NBD controls in an existing control panel.

Due to the uniqueness of the NBD to the transmission system, Emprimus provided operation and maintenance training to grid operators and

Maintenance staff. Commissioning took place over the next two months with successful energization in November.

"I often bemoan the sun's irate 'personality,' and maybe it was eager to put the White NBD to the test. In late February 2023, a moderate, double-coronal mass ejection that accompanied solar flares erupted from the sun, pointed at the Earth's orbital position," said Colson.

Just after midnight on Feb. 27, the solar storm rocked the Earth's magnetic field, giving rise to a strong GMD event. The National Oceanic and Atmospheric Administration's Space Weather Prediction Center, which uses a five-level scale similar to the hurricane wind-scale system, categorized the storm as a 'G3' GMD event.

"No worries, the White NBD was ready! On four separate occasions, the White NBD operated as expected, sensing the rise in GIC flow and automatically initiating its blocking during the space weather event that lasted about twelve hours," said Colson, who admits to eagerly awaiting the next coronal mass ejection event.

"With the White NBD in service and plans to extend the WAPA GIC monitoring network to improve situational awareness during GMD events, WAPA is well-positioned for whatever the sun cooks up," he added. □

Exhibit K

"Speed to Power on a Firm Foundation: Overcoming Dangerous Assumptions That Put America's Future at Risk." Center for Security Policy. November 2025.

Speed to Power on a Firm Foundation

*Overcoming Dangerous Assumptions
That Put America's Future at Risk*

BY **LT. COL. TOMMY WALLER**, USMC RET
President & CEO, Center for Security Policy
DOUGLAS ELLSWORTH, Secure the Grid Coalition

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COVER PHOTO: A utility manager drove out in the middle of the night to capture this photo of the aurora overhead while the GICs from the May 2024 "Gannon" solar storm were in full force - actively triggering SolidGround® over a dozen times at this substation - protecting a critical transformer behind those walls.

Executive Summary

Our Secure the Grid Coalition[1] has long worked to improve the security of our nation's most critical infrastructure – the electric grid. Importantly, we receive no funding from governments, foreign sources, the utility industry, or any company that can profit from protecting the grid. We exclusively serve the public interest, recognizing that a prolonged electrical blackout would cripple every one of our nation's 16 critical infrastructures, causing immense harm to our economy, our people, and our national security.

Dangerous assumptions about the invulnerability of our nation's transformers to a known risk – solar weather – make it 100% certain that such a blackout will occur in the future. Solar weather induces low frequency, quasi-DC currents in the Earth's crust that travel the path of least resistance, **entering the power grid from the ground** through transformer ground connected neutrals. These are known as geomagnetically induced currents, also called ground-induced currents (GICs). The E3 component of nuclear High Altitude Electromagnetic Pulse (HEMP) attack also produces GICs that can catastrophically damage the power grid via unprotected transformers.

Today, the United States' power grid is completely vulnerable to these harmful GICs. While the Trump Administration is wisely moving forward with a "Speed to Power" initiative to ramp up U.S. generation, it might be assuming that our current grid is secure and that the Nuclear Regulatory Commission (NRC) is responsibly addressing the GIC threat to current and future nuclear power generation. This report will prove that those assumptions are wrong. Our warning is like one issued by thought leaders for 2500 years, from the ancient Greek Aesop's Fables to Jesus Christ's "Sermon on the Mount":

Whatever you build will stand or fall depending on the firmness of its foundation.

Our report will demonstrate that DOE's exciting "Speed to Power" initiative and the future of American energy are at risk of failure <u>due to the lack of a firm foundation</u> protecting our electric grid. Absent protections, the next extreme solar storm could collapse the U.S. electric grid, resulting in millions of deaths—and potential loss of continuity of government. Comprehensive protection against solar storms would also mitigate the GICs generated from the E3 Pulse from a HEMP attack. Thus, nationwide GIC protection will rapidly bolster America's nuclear deterrence against peer adversaries and rogue nations seeking to exploit the asymmetric warfare benefits of HEMP attack.

Fortunately, commercially available, thoroughly validated, and cost-effective technology already exists to protect against both—the capacitive neutral blocking device known as SolidGround®. Deploying SolidGround® to protect America's roughly 6000 vulnerable transformers is a one-time cost of approximately $4 billion. This hardware protection will also save the U.S. approximately $10 billion in annual economic losses from the effects of routine solar weather. <u>This is a commonsense investment.</u>

Our present warning and recommendations are a re-address of those we voiced previously to DOE in August 2020[2], and to the previous Secretary of Energy in January 2022[3], June 2022[4] and April 2024[5]. Those leaders failed to act. Addressing the GIC threat today will require bold action from leaders at the federal, state, and local level. *We just hope these leaders will act in time.*

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[1] The Secure the Grid Coalition is a group of policy, energy, and national security experts dedicated to strengthening the resilience of America's electrical grid. It is parented by the Center for Security Policy, a 501(c)(3) nonprofit which receives no funding from governments, foreign sources, the electric industry, or any for-profit corporations involved in protecting the grid.

[2] https://securethegrid.com/wp-content/uploads/2021/02/STG-Coalition-Comments-on-DOE-RFI-24-Aug-2020.pdf

[3] https://securethegrid.com/wp-content/uploads/2025/11/STG-Coalition-Letter_to_DOE_on_Supply_Chain_RFI_Jan_2022.pdf

[4] https://centerforsecuritypolicy.org/wp-content/uploads/2022/06/STG-Coalition-Comments-SEAB-13June2022-Final.pdf

[5] https://securethegrid.com/wp-content/uploads/2025/11/STG-Coalition-Comments-SEAB-9April2024-with_Photos_and_Enclosure.pdf

NRC's Dangerous Decision

On May 7, 2025, the Nuclear Regulatory Commission published in the federal register[6] an extremely consequential decision with respect to the health, safety, and welfare of the American people and the environment of the continental United States. After more than fourteen years of deliberation, NRC denied an important Petition for Rulemaking submitted in February 2011, by the Foundation for Resilient Societies[7]. This Petition, docketed as PRM 50-96,[8] warned of the potentially catastrophic consequences associated with the long-term loss of offsite power for nuclear power plants, a realistic scenario given the vulnerability of America's electric grid to ground induced currents ("GIC") as a result of geomagnetic disturbances (GMDs) produced by the sun and intentional high-altitude electromagnetic pulse (HEMP) attack by enemies of the United States.

PRM-50-96 proposed long-term backup power for spent fuel pools at nuclear power plants because of the potential for human or mechanical error to interrupt power from emergency diesel generators (EDGs) currently employed for back-up power and for which the NRC requires only 7 days of fuel.

Were these EDGs to fail or run out of fuel during a protracted widespread grid outage, the electric pumps circulating cooling water around the spent nuclear fuel rods could fail, causing the water to boil off.

As the water boils off, the zirconium cladding on the radioactive rods reacts with steam, producing explosive hydrogen gas. At ~1,200–1,800°C, cladding fails, releasing radioactive fission products (cesium-137, iodine-131, etc.) into the "release." At ~2,200°C+, the fuel itself can melt, forming corium and potentially burning through the pool liner. The result could be an airborne radioactive release and possible hydrogen explosion.

Were a major solar storm to blackout the nation's grid for an extended period, numerous nuclear sites could be at risk of this scenario if their EDGs fail or run out of fuel.

This document is scheduled to be published in the Federal Register on 05/07/2025 and available online at https://federalregister.gov/d/2025-07899, and on https://govinfo.gov [7590-01-P]

NUCLEAR REGULATORY COMMISSION

10 CFR Part 50

[NRC-2011-0069]

Long-Term Cooling and Unattended Water Makeup of Spent Fuel Pools

AGENCY: Nuclear Regulatory Commission.

ACTION: Discontinuation of rulemaking activity; denial of petition for rulemaking.

SUMMARY: The U.S. Nuclear Regulatory Commission (NRC) is discontinuing a rulemaking activity, "Long-Term and Unattended Water Makeup of Spent Fuel Pools," and denying a petition for rulemaking. The petitioner requested that the NRC amend its regulations to require that nuclear power plant licensees ensure long-term cooling and unattended water makeup of spent fuel pools (SFPs). The purpose of this action is to inform members of the public that this rulemaking activity is being discontinued and to provide a brief discussion of the NRC's decision to discontinue the rulemaking and deny the aspects of the petition not previously addressed by the NRC.

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[6] NRC Ruling, "Long-Term Cooling and Unattended Water Makeup of Spent Fuel Pools,"
https://www.federalregister.gov/documents/2025/05/07/2025-07899/long-term-cooling-and-unattended-water-makeup-of-spent-fuel-pools
[7] Homepage: Foundation for Resilient Societies, https://www.resilientsocieties.org/
[8] Foundation for Resilient Societies, In the Matter of a Proposed Rulemaking Regarding Amendment of 10 CFR Part 50, "DOMESTIC LICENSING OF PRODUCTION AND UTILIZATION FACILITIES"
https://www.resilientsocieties.org/uploads/5/4/0/0/54008795/petition_for_rulemaking_resilient_societies_docketed.pdf

NRC Disregards USAF EDTF and GAO

Between 2018 and 2020, The White House, Department of Defense (DoD), Department of Energy (DOE), the NRC, and Air University hosted multiple interagency exercises examining the likelihood of prolonged electric power outages and consequent impacts to U.S. nuclear reactors and safety systems – including spent nuclear fuel. The unclassified findings and recommendations were published in Air University's special collection called The LeMay Papers.[9]
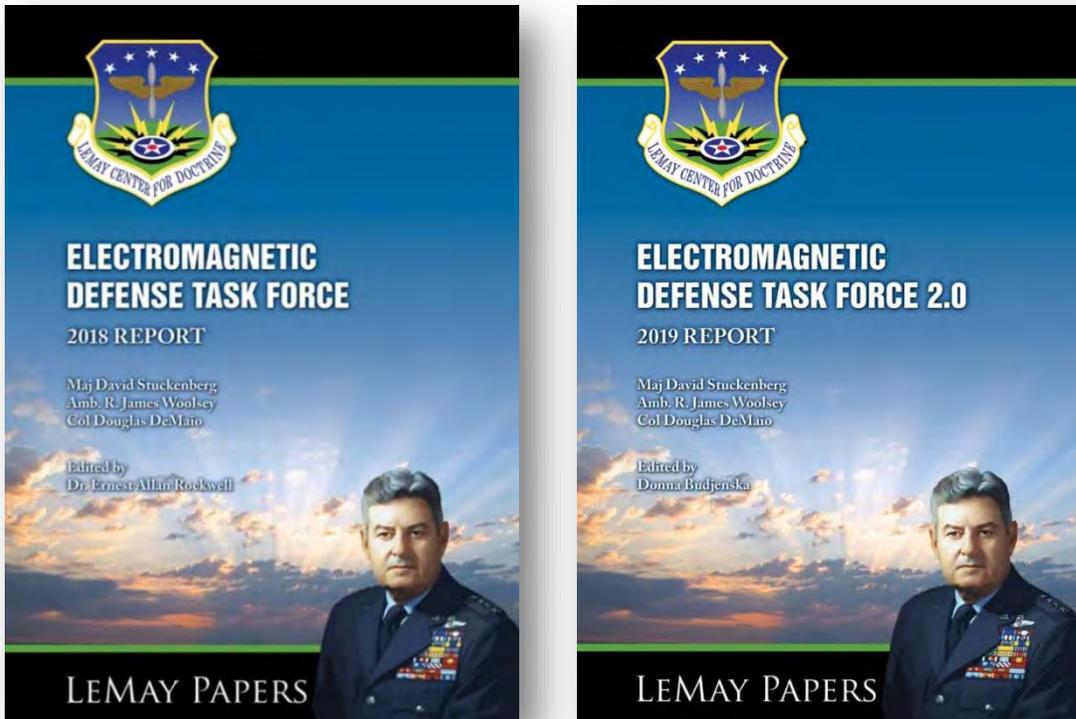
These reports[10] [11] and their annexes are the most read documents in Air University history, note the same vulnerabilities associated with previous reports on spent nuclear fuel and promote a series of similar recommendations, including that the NRC mandate the use of existing technologies to ensure long term cooling of spent nuclear fuel. In the EDTF's 2019 report, the NRC staff stated the following (p. 58):

> "*While the NRC expects spent fuel pools would boil off in days or weeks without electrical power for cooling, they do not expect EDG failures. Post-Fukushima safety improvements include instrumentation of spent fuel pools. Potential inability to obtain fuel delivery is a concern. Suggest the Department of Defense (DOD) provide a logistics option/guarantee.*"

There is no such DoD logistics option/guarantee in place to provide fuel to nuclear facilities following a protracted blackout, so NRC's decision to deny PRM-50-96 disregards the USAF EDTF's concerns.

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[9] Index: LeMay Papers, https://www.airuniversity.af.edu/AUPress/LeMay-Papers/
[10] Electromagnetic Defense Task Force 2018 Report, https://www.airuniversity.af.edu/Portals/10/AUPress/Papers/LP_0002_DeMaio_Electromagnetic_Defense_Task_Force.pdf
[11] Electromagnetic Defense Task Force 2019 Report, https://www.airuniversity.af.edu/Portals/10/AUPress/Papers/LP_0004_ELECTROMAGNETIC_DEFENSE_TASK_FORCE_2_2019.PDF

In September 2021, the Government Accountability Office[12] concurred with the USAF EDTF's concerns that spent fuel "—can pose serious environmental, public health, and security risks if not properly managed," warned that the "amount of spent fuel is growing by about 2,000 metric tons annually," and recommended Congressional action to and "develop a permanent disposal solution."

Since there is no permanent disposal solution, the nation must grapple with the fact that thousands of metric tons of this material are located across the country at nuclear sites, and much of it submerged in water that must keep circulating, using power from a grid assumed by the NRC to be invulnerable.

These NRC assumptions are based on major analytical flaws with respect to understanding and analyzing the GIC threat, on a reliance on a defective GIC protection standard, as well as dangerously optimistic assertions about transformer resilience.
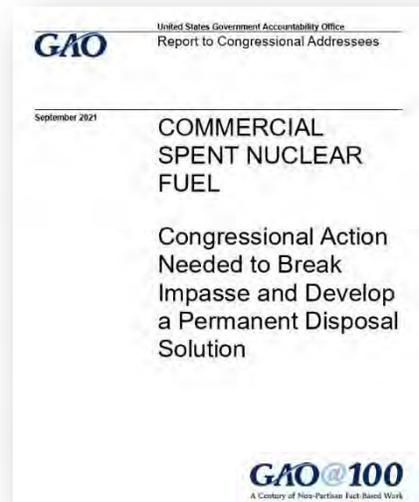
Understanding and Analyzing the GIC Threat

Geomagnetic Disturbances (GMDs) induce a quasi-DC current in the earth that travels the path of least resistance. These "geomagnetically induced currents" – also known as ground induced currents **(GICs) - invade the power grid from the earth** through the neutral to ground connection of high voltage transformers and travel across long transmission lines, causing damage to the largest components on our power grid — transformers, high voltage circuit breakers and large power generators — as well as the electric load.[13] The late-time component (E3) of nuclear high altitude electromagnetic pulse (HEMP) also produces GIC of 100's to 1,000's of Amps/phase.[14]

The field strength generating these GICs is measured in volts per kilometer (V/km) —a measurement that simply describes how strong the electric field is over a given distance—and directly correlates to the GIC magnitude expected to flow into the electric grid.[15] Example: a 2 V/km field strength inducing 100 Amps GIC at a specific location means that a 20 V/km event would generate 1000 Amps GIC at that location.

Thus the "V/km field strength" measurement is a big deal.

In the 1960s both the United States and the Soviet Union performed high-altitude nuclear tests that revealed the destructive power of HEMP. The Soviets chose a test location over an industrialized area

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[12] GAO, Report to Congressional Addressees, Commercial Spent Nuclear Fuel, "Congressional Action Needed to Break Impasse and Develop a Permanent Disposal Solution" https://www.gao.gov/assets/gao-21-603.pdf

[13] "Geomagnetic Disturbances (GMD) Impacts on Protection Systems", https://www.pes-psrc.org/kb/report/022.pdf

[14] Risk-Based National "Infrastructure Protection prioriities for EMP and Solar Storms" by George Baker, July 2017, Report to the EMP Commission & Congressional EMP Commission Report, "Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures" http://www.firstempcommission.org/uploads/1/1/9/5/119571849/recommended_e3_waveform_for_critical_infrastructures_-_final_april2018.pdf

[15] "The Lehtinen-Pirjola Method Modified for Efficient Modelling of Geomagnetically Induced Currents in Multiple Voltage Levels of a Power Network", https://angeo.copernicus.org/preprints/angeo-2021-63/angeo-2021-63-manuscript-version2.pdf

almost as large as Western Europe —present-day Kazakhstan —and proved that a single HEMP detonation produced strong GICs that severely damaged portions of the Kazakhstan electric grid.[16]

The V/km field strength is also dependent on geomagnetic latitude. GMD events tend to focus at the poles and lose some strength as they head toward the geomagnetic equator.[17] **HEMP E3 works in the opposite direction where the peak V/km field strengths are generated toward the geomagnetic equator** and begin to drop as they head toward the poles.[18] It is notable that the test location the Soviets focused on is at the specific geomagnetic latitude of Washington D.C.

After Congress established the EMP Commission in 2000, the Commission's scientists received important data from Russian scientists on those 1960s HEMP tests, determining that the Soviets achieved a "field strength" of **66 V/km**.[19]

In May 2025, the International Electrotechnical Commission (IEC) — a globally recognized organization that develops and publishes international standards for electrical, electronic, and related technologies, as well as grid operations —updated its recommended HEMP E3 protection standard (IEC 61000-2-9) to **85 V/km.**

Meanwhile, in the United States, there is no enforceable standard to protect our electric grid from the GICs generated by HEMP.

The only protection standard we have is for GMD. This standard, established by the North American Electric Reliability Corporation (NERC) and approved by the Federal Energy Regulatory Commission (FERC) is what NRC assumes is protecting the nation from GIC. This is a major analytical flaw and gravely dangerous assumption.

NRC Reliance on a Flawed NERC GIC Protection Standard

Since May 2013, the Federal Energy Regulatory Commission (FERC) has required the North American Electric Reliability Corporation (NERC) to set a reliability standard to protect high voltage transformers from the effects of Geomagnetic Disturbances (GMD). For the standard, FERC mandated that NERC set a so-called "Benchmark Geomagnetic Disturbance Event." This benchmark was to establish the maximum 1-in-100-year storm that electric utilities must protect against.

But when the NERC Standard Drafting Team developed the benchmark event, they did not use data on storms impacting North America – but rather used European data on magnetic fields during a 21-year period during which no major storms occurred. Nor did they collect data on past storm effects on critical

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[16] Emanuelson, J., "Soviet Test 184: The 1962 Soviet Nuclear EMP Tests over Kazakhstan" https://www.futurescience.com/emp/test184.html
[17] Popik, T., Baker, G., Harris, G., "Electric Reliability Standards for Solar Geomagnetic Disturbances", Comments submitted to the Federal Energy Regulatory Commission https://securethegrid.com/wp-content/uploads/2018/06/2017-Electric-Reliability-Standards-for-Solar-Geomagnetic-Disturbances.pdf
[18] Congressional EMP Commission, "Recommended E3 Waveform for Critical Infrastructures", https://securethegrid.com/wp-content/uploads/2018/05/2017-Recommended-E3-Waveform-for-Critical-Infrastructures-FINAL-April2018.pdf, 2017.
[19] Congressional EMP Commission, "Executive Report on Assessing the Threat from Electromagnetic Pulse (EMP)", 2017. https://securethegrid.com/wp-content/uploads/2018/05/2017-Executive-Report-on-Assessing-the-Threat-from-EMP-FINAL-April2018.pdf Executive Report on Assessing the Threat from EMP 18April2018

grid equipment such as high voltage transformers.[20] Beyond the above manipulation, the Drafting Team spatially averaged their findings which arrived at an insufficient defense-conservative benchmark to protect against only 8 volts per kilometer (8 V/km) beginning at the 60-degree geomagnetic latitude (over parts of Quebec) and then scaled down from there southward into the United States[21] (e.g. **only ~ 2 V/km for the Washington D.C. area at 49-degrees** which is the precise geomagnetic latitude as the 66 V/km achieved in 1962 by the Soviet HEMP testing over Kazakhstan).

This standard, TPL-007, has progressed through four iterations over nearly a decade and its latest version, TPL-007-4, established a well-developed set of requirements for GMD vulnerability assessment process, modeling timeframes, required models needed for complete analysis, and violation severity levels but remains critically deficient in TPL-007-1 as shown in "Attachment 1 Calculating Geoelectric Fields for the Benchmark and Supplemental GMD Events.[22]"

This is due to the Drafting Team's spatially averaging their GMD levels to artificially reduce the final "defense-conservative" benchmark to 8 volts per kilometer (8 V/km) over Quebec.

The inadequate benchmark has remained in place despite the science-based criticisms of both the sources and methods employed in its establishment. These well-founded and scientifically based criticisms came from both the nonprofit Foundation for Resilient Societies[23] and by the chief physicist for the Congressional EMP Commission, Dr. George Baker[24] before the U.S. Senate Committee on Homeland Security and Governmental Affairs.

In its 2017 report titled "Enhancing the Resilience of the Nation's Electricity System[25]," the National Academies of Sciences pointed out the need for "basic research" and "applied work to develop adequate simulations" to model severe events for the power grid, such as solar weather.

Two recent research papers published by USGS measuring the most consequential magnetic storms of the past century, the **1921 "Railroad Storm"** and the **1989 "Hydro-Quebec Storm,"** used data collected from magnetometer readings at specified sites.

The first of these is titled, **"Intensity and Impact of the New York Railroad Superstorm of May 1921."**[26]

> This study draws upon magnetometer readings and the failure of telephonic and telegraphic landline systems. This study uses these communications disruptions as a proxy for long-run interconnected conductors, as the electric power delivery topology in 1921 was not interconnected into the bulk power systems we have today. Using the example of the **railroad station that burned down due to overheated telegraph system** in Brewster, Connecticut, the CT160 survey station 27 km north of Brewster reported a geoelectric field of **19.40 V/km**, which

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[20] Popik, T., Testimony of the Foundation for Resilient Societies, March 1, 2016 Technical Conference, Docket No. RM15-11-000. https://www.ferc.gov/sites/default/files/2020-08/Popik-ResilientSocieties.pdf

[21] Waller, T., Ellsworth, D., written comment submitted to the Secretary of Energy Advisory Board, 2022. https://www.energy.gov/sites/default/files/2022-07/STG-Coalition-Comments-SEAB-13June2022-Final.pdf

[22] https://www.nerc.com/pa/Stand/Reliability%20Standards/TPL-007-1.pdf

[23] https://centerforsecuritypolicy.org/wp-content/uploads/2022/06/Appendix-A-Foundation-for-Resilient-Societies-Testimony-on-GMD-Protection-Standards.pdf

[24] https://centerforsecuritypolicy.org/wp-content/uploads/2022/06/Appendic-C-2019-George-H-Baker-Written-TestimonyFINAL.pdf

[25] http://nap.naptionalacademies.org/24836

[26] Love, J., Hayakawa, H., Cliver, E., "Intensity and Impact of the New York Railroad Superstorm of May 1921", 2019. https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002250

is more than 7 times the benchmark of 2.4 V/km per TPL-007-4 for the same geomagnetic latitude.

The most recent of these two studies (May 2022) is titled "Mapping a Magnetic Superstorm: March 1989 Geoelectric Hazards and Impacts on United States Power Systems."[27]

Geomagnetically Induced Currents (GICs) realized during the magnetic storm of March 1989 caused a blackout in Québec, Canada. The highest measured GICs occurred in the Mid-Atlantic and Northeast United States, where they **caused operational interference for electric-power companies and catastrophically damaged a high-voltage transformer.** (See image below)

March 1989 magnetic storm damage to a high-voltage transformer at a nuclear power center in Salem, New Jersey.

This study provides guidance where utility companies might concentrate their efforts to mitigate the impacts of future magnetic superstorms. The 1989 storm had its greatest impacts from Ground Induced Currents (GICs) in those regions of lowest earth crust conductivity. These regions are the highly populated Mid-Atlantic states through New England, and the Upper Midwest region.

This study of 1989 magnetic storm produced field amplitude peaks 1-minute resolution of **21.66 V/km** in Maine and **19.02 V/km** in Virginia[28] and **17.33 V/km**[29] in Connecticut. The Upper Midwest region was measured at **12.28 V/km**, at survey site MNB36 in Minnesota.[30]

These data points far exceed the scaled down V/km benchmarks adopted in TPL-007-4.

GICs from Solar Storms Can Create Transformer Failures LATER:

It should be noted that the damaging impacts of Geomagnetic Disturbances do not have to manifest immediately, as the failures often manifest from cumulative effects, months after an event that caused the

[27] Love, J., Lucas, G., Rigler, J., Murphy, B., Kelbert, A., Bedrosian, P., "Mapping a Magnetic Superstorm: March 1989 Geoelectric Hazards and Impacts on United States Power Systems", 2022. https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW003030
[28] Ibid., p1 https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW003030
[29] Ibid., p 19 https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW003030
[30] Ibid., p 11 https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW003030

damage. For example, there were 12 nuclear power generating stations which suffered transformer failures within 25 months of the 1989 Hydro-Quebec Geomagnetic event. These nuclear plants were:[31]

•	WNP 2	•	10 Susquehanna
•	South Texas	•	Surry 1
•	Zion 2	•	Oyster Creek
•	D.C. Cook 1	•	Salem
•	Shearon Harris	•	Peach Bottom
•	Nine-Mile	•	Maine Yankee

Transformer Damage from the 2003 South Africa Solar Storm

In 2003, a very-low-level solar event occurred that affected South Africa's grid. Joseph H. McClelland, director of the Federal Energy Regulatory Commission's Office of Energy Infrastructure Security, said it was one-fiftieth the size of the 1921 "Railroad Storm" event, but it lingered on for a period of days. Mr. McClelland continued in his testimony before a 2015 U.S. Senate Committee hearing, that while the grid in South Africa did not collapse immediately, it did damage expensive utility substation equipment that terminally failed over a period of time. Instead of immediate damage, utility equipment saw prolonged exposure to the GIC event and, over a period of months. According to McClelland, "12 transformers were lost due to that event."[32]

GMD/ EMP Impacts Will Be Worse Today than 1989 and 2003

The **March 1989 Solar Storm has been deemed** by many in the scientific community, including Dr. Love in the most recent USGS Study, to represent **a "1-in-40-year" storm**.

In the years after 1989 and 2003, the electric power grid continued to expand, becoming more interconnected and operating at higher voltage and current levels. According to a 2013 report from Lloyd's, "The higher voltage lines offer less resistance, and therefore larger [GIC] currents flow relative to lower voltage lines when exposed to the same surface electric fields."[33] Therefore, a solar storm of the intensity of 1989 with identical geospatial and time dependencies would be expected to debilitate the power grid more severely than the 1989 storm. Again, it was deemed to be a 1-in-40-year storm.

Since the directive of FERC was to establish a benchmark for a 1-in-100-year magnetic storm the need for a higher benchmark is self-evident.

Additional Visual Aids:

Below are images depicting the differences between the NERC standard "benchmark" and "scaling factor" **(in black)** and actual measured data **(in red),** with an excerpt from page 29 of NERCs TPL-007-4. Also below is a map depicting the specific geomagnetic latitude of the Soviet HEMP test in 1962 over Kazakhstan which is the same geomagnetic latitude as Washington D.C. [See images on next page].

[Note: More information on the dangerously lethargic FERC/NERC rulemaking process is provided below in Appendix 1.]

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[31] Page 268, Foundation for Resilient Societies TPL-007-1 Appeal, https://acrobat.adobe.com/id/urn:aaid:sc:VA6C2:8bd5c492-06ae-4959-a449-9a28c49b7606, accessed April 7, 2024

[32] Committee on Homeland Security and Governmental Affairs, United States Senate, "Protecting the Electric Grid from the Potential Threats of Solar Storms and Electromagnetic Pulse", 2015. https://www.govinfo.gov/content/pkg/CHRG-114shrg22225/pdf/CHRG-114shrg22225.pdf

[33] Lloyd's, "Solar storm Risk to the North American Electric Grid", 2013. https://assets.lloyds.com/assets/pdf-solar-storm-risk-to-the-north-american-electric-grid/1/pdf-Solar-Storm-Risk-to-the-North-American-Electric-Grid.pdf

1989 Storm Field Strength (V/km) per Geomagnetic Latitude

NERC Standard vs. measured data

NERC Standard Benchmark

60°

8 V/km

54°

4 V/km → 21.66 V/km

50° → 17.33 V/km

2.4 V/km

45° → 19.02 V/km

1.6 V/km

40°

0.8 V/km

Table 2: Geomagnetic Field Scaling Factors for the Benchmark and Supplemental GMD Events	
Geomagnetic Latitude (Degrees)	Scaling Factor1 (α)
≤ 40	0.10
45	0.2
50	0.3
54	0.5
56	0.6
57	0.7
58	0.8
59	0.9
≥ 60	1.0

NERC TPL-007-4 (p. 29)

TPL-007 begins with their benchmark (8 V/km @ 60 °) then scales down per geomagnetic latitude by multiply by the Scaling Factor1 - Table 2 (above) Example: 50° = 2.4 V/km [8 x 0.3]

"We conclude that using the Quebec model leads to underestimation of peak geoelectric field amplitudes for the March 1989 storm..."

-Space Weather - 2022 - Love - Mapping a Magnetic Superstorm March 1989 Geoelectric Hazards and Impacts on United States

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1962: The Soviets conducted two high-altitude nuclear test(s) over Kazakhstan, specifically on either side of the *geomagnetic latitude* of **49°**: 1st Test @ **49.10°** and 2nd Test @ **48.92°**

Is it a coincidence the Soviets tested at the same **49°** as Washington D.C.?

60 years ago, the Soviets achieved an EMP **E3**B field strength of

66 V/km @ 49°

Vs.

The GMD standard for Washington D.C. considers only

2 V/km @ 49°

Geomagnetic Latitude Map

60°

55°

50°

49° — 49° — ★ — 49°

Washington D.C.

45°

40°

35°
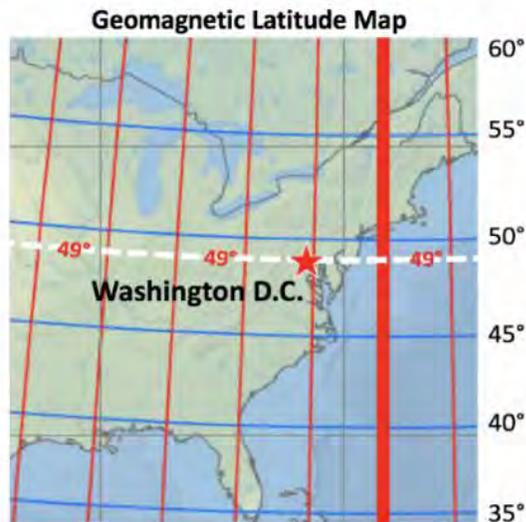
-Report of the Commission to assess the threat to the United States from EMP attack, **"Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures"**, Executive Summary, July 2017, **Conclusions - pg. 24** 10

NERC Standard vs. GIC Threat
GIC Magnitude Comparison

The electric field strength of GMD and E3 HEMP events are measured in volts per kilometer (**V/km**) which directly relates to how large the ground induced currents (**GIC**) will be.

Field Strength (V/km)

- 8 — NERC Benchmark set @ 60° geomagnetic latitude (Quebec, Canada)
- 2 — NERC Standard for **Washington D.C. ~ 2 V/km** @ 49° across center of U.S.
- 0.8 — NERC Standard for **Texas, Florida**... **0.8 V/km** @ 40° across southern states
- 20 — NY Railroad Solar Storm 1921 (**20 V/km**)
- >20 — Carrington Event 1859 (**> 20 V/km**)
- 66 — Soviet E3 HEMP Tests 1962 (*achieved* **66 V/km** @ 49°)
- 85 — Congressional EMP Commission E3 HEMP (**85 V/km** for Continental U.S.)
- >85 — **IEC E3 HEMP Standard:** updated May 2025 (**85 V/km** *and above*)

Moreover, geomagnetic storm intensity as reported by NOAA and others that study the solar phenomena is measured in nanoteslas (nT) for purposes of comparing events. This does not correctly compare, nor is it the function of solar scientists to compare, the extent of damage that a solar event could inflict on the power grid. The correct measurement to compare the intensities of ground induced currents (GIC) from a solar event is nanotesla per minute (nT/min). It is the rate of change that is the determining factor in the magnitude of ground-induced currents. According to Faraday's Law of Induction, a faster rate-of-change in magnetic flux results in a greater induced voltage. The nT comparison of solar storms is inaccurate and misleading when considering the space weather threat to our power grid. Example: it is the nT comparison that leads some to the belief that the 1989 Quebec Storm was 50% the estimated size of the 1859 Carrington Event when in actuality it was less than 10% the size as it relates to GIC magnitude due to the rate of change (nT/min.)

NRC Dangerous Assumptions on Transformer Resilience to GIC

In 2018, Mr. Scott McBride, Infrastructure Security Manager at the Department of Energy's Idaho National Laboratory (INL), testified[34] before the US Senate, warning that "The Nation's High Voltage (HV) and Extra High Voltage (EHV) power grid contains a few thousand large power transformers which are potentially vulnerable to the threat of GMD events" and that "These transformers are very expensive to build and typically have long lead times of eighteen to twenty-four months."

Since then, production lead times on large power transformers have only grown.

Last year, **Utility Dive[35]** reported that the National Electrical Manufacturers Association (NEMA) warned that "delivery of a new transformer ordered today could take up to three years" and Hitachi Energy specified that, "transmission scale unit lead times are now three years to six years, with specialized transformers taking the longest time."

Those large transmission scale transformers mentioned by Hitachi are custom built, cost tens of millions of dollars, and are the MOST vulnerable to GICs, per their design.

Yet, in **NRC's decision to deny PRM-50-96**,[36] the commission stated the following:

> *"Currently, more than 80 percent of extra high voltage transformers are resistant against the effects of geomagnetically induced currents."*

This statement by the NRC fails to consider the transformer design and real-world operational conditions of power transformers in the U.S. electric grid. Conditions that need to be considered in the effects of GIC on power transformers are the age of the power transformer, its insulating oil condition, and transformer loading at the time of the GIC. These are all factors in the susceptibility of power transformer damage and failure.

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[34] Statement of Scott A. McBride, Infrastructure Security Manager: National & Homeland Security, Idaho National Laboratory, before the United States Senate Homeland Security & Governmental Affairs Committee, September 13, 2018. https://www.hsgac.senate.gov/wp-content/uploads/imo/media/doc/Testimony-McBride-2018-09-13.pdf

[35] Utility Dive, "Transformer supply bottleneck threatens power system stability as load grows", Feb. 12, 2025. https://www.utilitydive.com/news/electric-transformer-shortage-nrel-niac/738947/

[36] Nuclear Regulatory Commission denial of PRM 50-96, Docket ID NRC-2011-0069, 2025. https://www.nrc.gov/docs/ML2427/ML24275A091.pdf

The **"Large Power Transformer and The U.S. Electric Grid"**[37] publication by the Department of Energy (DOE) Office of Electricity stated:

> "*The average age of installed LPTs in the United States is approximately 38 to 40 years, with 70 percent of LPTs being 25 years or older. While the life expectancy of a power transformer varies depending on how it is used, aging power transformers are potentially subject to an increased risk of failure.*"[38]

The aging of power transformers in the U.S. Electric Grid increases their susceptibility to GIC due to insulating oil condition and coil conditions. Older power transformers are subject to mechanical stress of the coil due to inrush currents, system faults, and coil degradation.[39] Additionally, transformer loading at the moment of a GMD event will contribute to the power transformer's susceptibility to GIC.[40] Mechanical stress of the coil in power transformers increases the susceptibility of transformer damage and failure due to GIC.[41]

Extra High Voltage (EHV) power transformers use an insulating medium for the transformer coil. Most large power transformers use mineral oil for the power transformer insulating and cooling medium.[42] A lesser proportion of large power transformers use bio-based oil, such as FR3, which has a higher flashpoint and is considered environmentally better due to its biodegradability.[43] However, this insulation medium is still susceptible to forms of contamination that will make it susceptible to the effects of GIC.[44] Given the age of the majority of the power transformers in the U.S. Electric Grid, it is necessary to question the monitoring, testing and maintenance of power transformers in the U.S. Electric Grid.

Maintenance of power transformers includes insulating oil testing to determine the condition of the insulating oil. Necessary analysis includes Dissolved Gas Analysis (DGA), which detects arcing, overheating and insulation failure, Moisture Analysis, Dielectric Breakdown Voltage, which determines oil insulating capacity, Flash Point, Interfacial Test, which tests oil contamination, and Furan Test, which determines the paper content in the insulating oil to determine coil insulation breakdown.

As power transformers age the condition of the insulating oil becomes a critical factor in enhancing the effect of GIC in damage and power transformer failure. The need to test power transformer insulating oil and replacement is a key factor in the power transformer's susceptibility to the damaging effects of GIC.

In a **Market Reports World**[45] report titled "Transformer Oil Testing Market Size, Share, Growth, and Industry Analysis, By Type (Dissolved Gas Analysis, Moisture Analysis, Dielectric Breakdown Voltage,

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[37] U.S. Department of Energy, Infrastructure Security and Energy Restoration
Office of Electricity Delivery and Energy Reliability, "Large Power Transformers and the U.S. Electric Grid", 2014 Update.
https://www.energy.gov/sites/default/files/2014/04/f15/LPTStudyUpdate-040914.pdf

[38] https://www.energy.gov/sites/default/files/2014/04/f15/LPTStudyUpdate-040914.pdf - page vi

[39] Steurer, M., and Frohlich, K., "The impact of inrush currents on the mechanical stress of high voltage power transformer coils," in *IEEE Transactions on Power Delivery*, vol. 17, no. 1, pp. 155-160, Jan. 2002 https://ieeexplore.ieee.org/document/974203

[40] NERC, "2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System", https://www.nerc.com/globalassets/programs/rapa/gmd/reference-documents/nerc_gmd_report_2012.pdf

[41] DOE, "Large Power Transformer Resilience", 2024, https://www.energy.gov/sites/default/files/2024-10/EXEC-2022-001242%20-%20Large%20Power%20Transformer%20Resilience%20Report%20signed%20by%20Secretary%20Granholm%20on%207-10-24.pdf

[42] Ibid.

[43] Cargill, "Dielectric Fluids", https://soltexinc.com/wp-content/uploads/2024/01/FR3-Data-Sheet.pdf

[44] Department of Electrical Engineering, Blekinge Institute of Technology, "Properties of Transformer Oil that Affect Efficiency" https://www.diva-portal.org/smash/get/diva2%3A829952/FULLTEXT01.pdf

[45] Market Reports World, "Transformer Oil Testing Market Size, Share, Growth, and Industry Analysis, By Type: Regional Insights and Forecast to 2033", https://www.marketreportsworld.com/market-reports/transformer-oil-testing-market-14716359#:~:text=Transformer%20Oil%20Testing%20Market%20Overview.%20The%20Transformer,CAGR%20of%205.8%25%20from%202025%20to%202033.

Flash Point, Interfacial Tension, Others), By Application (Mineral Oil, Non Mineral Oil), Regional Insights and Forecast to 2033" (2024) the report found the following concerning utility power transformer insulating oil testing:

> "*In the United States, over 60% of utility companies have integrated transformer oil test data into centralized asset management systems.*"

While the percentage is above half of the utilities in the U.S., it still does not indicate the frequency of testing, the test results, or the amount of maintenance done to improve the insulating oil in the large power transformers. If large power transformers insulating oil is not tested on a regular, consistent interval and maintained, then the condition of the large power transformer, its core and coil will degrade. This, combined with the age of the core and coil of the transformer, will increase the susceptibility of the large power transformer to GIC.

Additionally, when the total number of large power transformers is considered, the 40% of utilities that give no indication of power transformer insulating oil testing and maintenance is a cause for grave concern with respect to those large power transformers' susceptibility to GIC.

All these factors taken together, indicate that the susceptibility of large power transformers in the U.S. electric grid is not negligible and that they are not resistant to GIC-induced damage and failure. In review of the real-world operations of the U.S. electric grid by way of its large power transformers, the view taken by the NRC that "*Currently, more than 80 percent of extra high voltage transformers are resistant against the effects of geomagnetically induced currents.*" is misleading and without foundation.

GICs Could Spell the Death of Our Nation

In the 2008 House Armed Services Committee hearing, Commission Chairman Dr. William R. Graham and Commissioner Dr. Lowell Wood emphasized that the U.S. population is overwhelmingly urbanized and non-agricultural, at approximately 83 percent, meaning only a small fraction has the means to survive without the grid. Dr. Graham noted that a post-EMP society would resemble a pre-industrial, rural economy in which perhaps only 10% of the population could sustain itself, "about 30 million people.[46]"

According to a 2017 report by the **U.S. Senate Committee on Homeland Security**,[47]

> "A successful nuclear electromagnetic pulse (EMP) attack against the United States **could cause the death of approximately 90 percent of the American population**. Similarly, a geomagnetic disturbance (GMD) could have equally devastating effects on the power grid."

This projection that as much as 90% of the U.S. population could perish within a year after a nationwide loss of electricity was not based on the direct physical effects of EMP, but on the cascading collapse of every life-sustaining system in modern society once power is removed.

The United States operates on highly interdependent, "just-in-time" supply chains with minimal reserves of food, fuel, medicines, and treated water. Diesel supplies—critical for transportation, generators, water

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[46] Source: "Threat Posed by Electromagnetic Pulse (EMP) Attack", Committee on Armed Services, House of Representatives, 2008. https://www.congress.gov/110/chrg/CHRG-110hhrg45133/CHRG-110hhrg45133.pdf]
[47] Report of the Committee on Homeland Security and Governmental Affairs, United States Senate and its Subcommittees, 2017. https://www.govinfo.gov/content/pkg/CRPT-115srpt12/pdf/CRPT-115srpt12.pdf

treatment, and hospital operations—exist largely at point of sale or in transit and would be rapidly exhausted. Without electricity, water and sanitation systems fail, food distribution halts, hospitals lose backup power without fuel, and fuel production ceases. The resulting shortages, disease, and inability to maintain order and social stability quickly lead to law of the jungle in urban environments.

In an effort to examine the analysis of the Senate and EMP Commission, the U.S. Air Force Electromagnetic Defense Task Force asked for the assistance of Air Force Veteran and Survival Evasion Resistance and Escape (SERE) Instructor Jonathan Hollerman. At the request of EDTF Staff, Hollerman published his findings in an eye-opening report on the psychology and physiology of Human Desperation, Starvation, and living in a world Without-Rule-of-Law.

The report, originally published in 2019 for the USAF EDTF, was updated in 2023, and titled **Grid Down: Death of a Nation**.[48] The report proved analytically that a widespread and protracted blackout would indeed lead to the death of most of America's population – likely more than predicted by the Congressional EMP Commission and the U.S. Senate. This underscores the grave need to protect our grid from the GIC threat ignored by NRC.
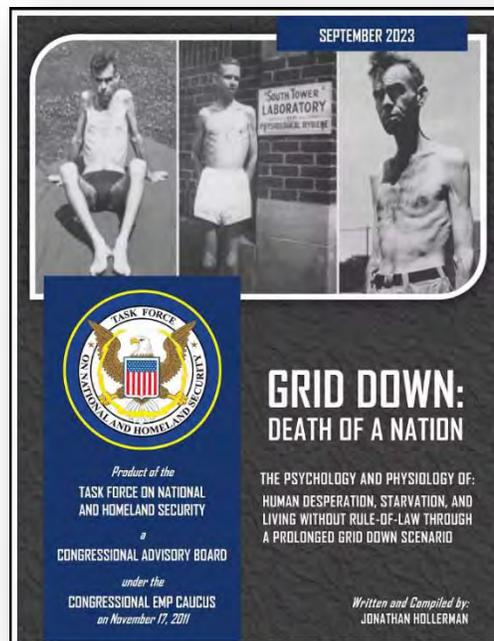
GICs Cost America Billion(s) of Dollars Annually

The fact that a HEMP or large solar storm could devastate these critical assets is only part of the bad news.

The other bad news is that even minor solar storms produce harmful GICs that pass through these "high risk design" large power transformers, causing them to induce harmonics which ruin downstream equipment —producing economic losses in the United States of **approximately $10 billion each year**.

That statistic comes from the rigorous statistical analysis of the highly credible Swiss-based global insurer Zurich, based on insurance claims filed, in its 2015 study titled "Electric Claims and Space Weather",[49] which drew upon previous joint research[50] between Zurich, Lockheed Martin, and the National Oceanic and Atmospheric Administration (NOAA).

[48] Hollerman, J., GRID DOWN: Death of a Nation, 2023. https://www.griddownconsulting.com/grid-down-report
[49] Zurich, "Electrical Claims and Space Weather: Measuring the visible effects of an invisible force, 2015. https://centerforsecuritypolicy.org/wp-content/uploads/2022/06/Appendix-F-2015Zurich-ElectricalClaimsandSpaceWeather.pdf
[50] C. J. Schrijver, R. Dobbins2, W. Murtagh, S. M. Petrinec, "Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment", 2014. https://centerforsecuritypolicy.org/wp-content/uploads/2022/06/Appendix-E-Space-Weather-2014-Schrijver-Assessing-the-impact-of-space-weather-based-on-insurance.pdf

Adjusted for inflation, the Zurich estimates suggest America is now, in 2025 dollars, suffering $15 billion in losses annually because we've gotten it wrong and failed to block these routine GICs from entering the grid.

"Operating Procedures"
Are Not the Answer to GIC Threat

Despite the grave risks to nuclear safety and to the very survival of the American people, the electric power industry claims that "operating procedures" can mitigate the known hazards of GIC. It is important to note that **operating procedures cannot block GIC from entering an operating grid**. Instead, these procedures attempt to mitigate GIC hazards after they have entered and cascaded across the grid. One industry countermeasure is the use of "Static VAR Compensators" or "SVCs" which are traditionally used to help grid operators stabilize the system.[51]

Before explaining how this procedure can actually be counterproductive, it is worth reviewing how GICs from GMD and E3 HEMP damage the grid.

From the perspective of transformer physics, both GMDs and HEMP E3 events induce low-frequency, quasi-direct currents **in the earth** (GIC) which travel the path of least resistance and invade the electric power grid through the ground connected neutrals of transformers and travel across transmission lines. Transformers are designed exclusively for alternating current (AC) operation, with magnetic cores that function optimally under balanced, sinusoidal conditions. When direct current enters the windings, it biases the core toward saturation on one half of the AC waveform. This "half-cycle saturation" produces three major harmful effects: generation of harmonics that disrupt the stability of the wider grid and damage components, intense localized heating of windings and structural components, and reactive power consumption.

Harmful intensities of these harmonics increase as GIC increases and are further enhanced as they travel through transmission into progressively lower voltage distribution paths, causing damage and wear on customers' equipment. The heating effect can damage insulation, accelerate aging, or in extreme cases cause catastrophic transformer failure. The harmonic distortion and reactive power consumption triggered by saturation can depress transmission voltages over large areas.[52] [53] [54]

Employing SVCs – A Countermeasure That Increases the Damage

As transmission voltages over large areas are depressed, system operators are forced to deploy voltage-supporting capacitors known as "Static VAR Compensators" or "SVCs."

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[51] Midea-Hiconics, "Understanding SVC: The Role of Static Var Compensators in Modern Power Systems", 2024. https://www.hiconics-global.com/understanding-svc-the-role-of-static-var-compensators-in-modern-power-systems.html

[52] Congressional EMP Commission, "Critical National Infrastructures", 2008. https://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf

[53] NERC, 2012 Special Reliability Assessment Interim Report: "Effects of Geomagnetic Disturbances on the Bulk Power System", https://www.nerc.com/globalassets/programs/rapa/gmd/reference-documents/nerc_gmd_report_2012.pdf

[54] Jointly-Commissioned Summary Report of the North American Electric Reliability Corporation and the U.S. Department of Energy's November 2009 Workshop: "High-Impact, Low-Frequency Event Risk to the North American Bulk Power System", 2010. https://www.energy.gov/sites/prod/files/High-Impact%20Low-Frequency%20Event%20Risk%20to%20the%20North%20American%20Bulk%20Power%20System%20-%202010.pdf

This procedure can benefit the operator during small scale solar impacts but are precisely the wrong thing to do during large-scale solar or E3 HEMP.

With SVCs in place, the problems not only remain but are exacerbated as GIC and induced harmonics increase, as does the duration of a continuing event. VAR support is a very dangerous approach for large GIC events.

As grid operators are attempting to solve one issue (VAR loss/voltage drop) they are opening a host of other issues increasing the likelihood of a catastrophic outcome for critical grid assets such as transformers, circuit breakers, power generators and the load.

According to NERC:[55]

> "Reactive power absorption from saturated transformers would tend to lower system voltages. Tripping of reactive power support from capacitor banks and SVCs due to high harmonic currents at a time when the saturated transformers increase the VAR demand, creates the scenario for voltage collapse."

This supports the idea that one mechanism (voltage drop due to reactive losses) is being addressed by operators, but **additional stress** (harmonics, saturated transformers, loss of reactive support) appears.

According to EPRI:[56]

> "The most vulnerable power equipment includes **capacitor banks and synchronous generators**. **High harmonic current levels can either damage this equipment or force their protective tripping. Capacitor banks and generators** supply the majority of a system's **reactive power resources**, and **their tripping or failure remove reactive sources at a time when the grid is subjected to the significantly increased reactive power demands** of the GIC-saturated transformers."

Thus, **operating procedures to utilize SVC's or turn up generation and provide replacement VARs** to make up for VAR losses (due to transformers half-cycle saturating from GIC) can help prop up the voltage and **prevent grid collapse during small GIC events but puts the power grid at greater risk of catastrophic damage during a large GIC event**.

Moreover, GIC induced harmonics and risk of thermal damage increase as GIC increases and equipment is exposed to GIC for a longer period of time. Relying on VAR support to prop up the voltage during a large GIC event to keep the grid up longer as GIC continues to climb puts components across the grid at greater risk of permanent damage (including at the Distribution level as harmonics generated at the Generation and Transmission level continue to grow as they travel towards load).

From a NERC-hosted EIS Council Summit Transcript:[57]

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[55] Op. Cit.. NERC, 2012, "High-Impact, Low-Frequency Event Risk to the North American Bulk Power System"
https://www.nerc.com/globalassets/programs/rapa/gmd/reference-documents/nerc_gmd_report_2012.pdf
[56] EPRI, "Analysis of Geomagnetic Disturbance (GMD) Related Harmonics", 2014.
https://www.epri.com/research/products/000000003002002985
[57] Transcripts: The Electric Infrastructure Security Summit III, London, 2012
https://www.nerc.com/globalassets/programs/rapa/gmd/reference-documents/london_transcript_112012.pdf

"In general while this is defining the envelope here and we can see it goes up in the case of some of the transformers as much as about 60 amps per phase the reality is a severe geomagnetic storm as we know from the simulations done from collected data making intelligent extrapolations from that collected data, we know that there will be transformers which have for some of the most severe and extreme events that we're aware of much higher GIC levels than 50 amps per phase, maybe in some cases approaching nearly 1,000 amps per phase. We begin to remove some doubt about what may happen to these design transformers."

We can see that it is critical to block GIC and prevent it from entering the power grid. Keeping the grid up by way of VAR supply will lead to the inevitable decision to intentionally open phase breakers (or unintentionally due to harmonics or E1) and will be at the worst possible time with high GIC across those breakers. AC Circuit Breakers require "zero crossings" to break AC. They are <u>not</u> designed to break GIC. Attempting to utilize AC breakers to break GIC is a misapplication and can lead to catastrophic damag*e*.

"Missile Defense" Is Not the Answer to GIC Threat

While missile defense systems play an important role in protecting the United States from certain classes of strategic attack, they are not, and cannot, be considered a solution to the threat posed by the E3 component of high-altitude electromagnetic pulse (HEMP) weapons. Understanding these limitations is critical for policymakers, because overreliance on missile defense as a singular protective measure risks leaving the nation exposed to catastrophic grid failure.

Effective Missile Defense is Not the Solution

To recap: Unlike lower-altitude nuclear strikes, high-altitude nuclear detonations do not cause blast or thermal effects at ground level but instead induce powerful electromagnetic fields over continental-scale areas. North America is surrounded by oceans making it the perfect EMP target as the enemies of the United States will not impact their own grid or their allies when attacking with high-altitude electromagnetic pulse. The E3 component of this high-altitude electromagnetic pulse which can last for more than 1,000 seconds (IEC 61000-2-9, Edition 2.0 2025-05), mimics the quasi-direct current effects of a severe geomagnetic storm, but with field levels ten times stronger than a severe GMD event. All of this drives extreme ground induced currents (GICs) into the grid and threatens widespread transformer saturation, harmonics, damage and collapse of the bulk power system.

Payloads in Satellites in Low-Earth Orbit are at a Prime Altitude for E3 HEMP

Peak E3 HEMP field strength (resulting in maximum GIC) only requires a small 100-kiloton nuclear weapon yield, burst at altitudes between 140 and 500 kilometers above the Earth's surface. The required altitude for maximum E3 and the weapon's light weight make low-orbiting satellites an optimal delivery system for this sort of attack. Missile defense systems, such as Israel's Iron Dome or the U.S. Ground-based Midcourse Defense program, are designed primarily to intercept incoming ballistic missiles during the midcourse or terminal phases of ballistic missile flight. While these systems can, in theory, intercept a missile intended for a high-altitude detonation, several factors limit their real-world effectiveness against this type of threat:

First, **a missile successfully intercepting a nuclear weapon at high-altitude can cause an E3 HEMP event** as these E3 weapons can and are designed with special fusing mechanisms[58] to detonate upon interception and/or sensor detection of an approaching missile.

Second, a nuclear weapon disguised as a low orbiting satellite would provide many attack opportunities. Low orbiting satellites are the easiest to launch and there is no effective way to detect a nuclear warhead "dressed" inside of a satellite as many 1,000s cross over the U.S. each day.
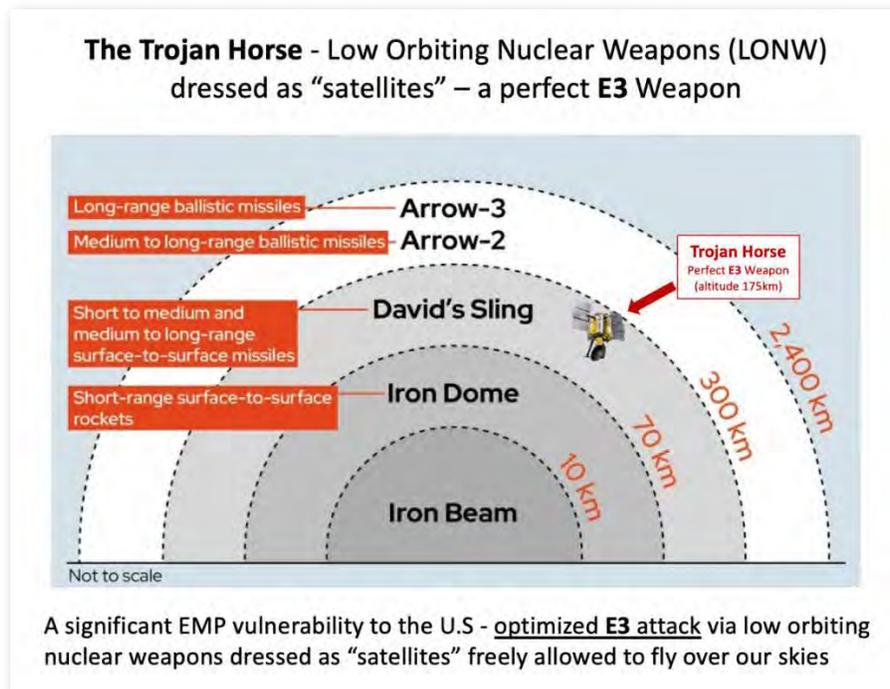
Third, trajectory and timing present unique challenges. An adversary could use a **Fractional Orbital Bombardment System (FOBS)**[59] such as the Soviet Union developed during the Cold War, or a similar delivery platform to place a nuclear warhead into low-Earth orbit, then de-orbit it over the continental United States from an unexpected direction, such as from the south. This approach could bypass much of the U.S. early-warning radar coverage, which is optimized for threats approaching from the north, and significantly compress the decision and intercept window.

Fourth, multiple attacks or the use of decoys could overwhelm defensive systems. An adversary need not achieve perfect accuracy with multiple warheads or payloads; a single nuclear weapon detonated at high-altitude over the continental U.S. will have nationwide effects on the grid. If just one of several inbound payloads evades interception, the attack succeeds in its objective of generating E3 ground induced currents in our electric grid.

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[58] "Electromagnetic Pulse Threats to U.S. Military and Civilian Infrastructure", Hearing before the Military Research and Development Subcommittee of the Committee on Armed Services, House of Representatives, 1999.
https://commdocs.house.gov/committees/security/has280010.000/has280010_0.htm
https://www.empcommission.org/docs/empc_exec_rpt.pdf
[59] Thomas L. Hughes to the Secretary, "Tests of Soviet Fractional Orbital Bombardment System (FOBS)," Intelligence Note 669, 14 August 1967.
https://nsarchive.gwu.edu/document/21718-document-28-thomas-l-hughes-secretary

Fifth, the geography of missile defense coverage is not uniform. Current U.S. interceptors are concentrated in specific locations, leaving potential gaps in coverage for trajectories that exploit the curvature of the Earth or blind spots in radar networks, or as described, coming from the south with a northern trajectory.

Missile Intercept Cannot Halt/Deter the Vagaries of the Sun

Finally, even the most effective defense systems cannot address the other origin of GIC threats: our sun. A Carrington-class coronal mass ejection would produce GIC effects over much the same geographic footprint as an E3 HEMP event, but no missile defense system can intercept or deflect a burst of charged particles emitted by the Sun.

This is why a dual-track approach is essential: continued investment in missile defense to intercept certain classes of threats, combined with the deployment of proven, cost-effective GIC-blocking technology across critical grid assets to protect against E3 HEMP and GMD. Without the second component of grid hardening, the United States remains exposed to a scenario in which an E3 HEMP attack, or the occurrence of a severe solar storm, could lead to nationwide power collapse.

The Validated Solution to GIC Threat is Available

As Mr. Scott McBride of Idaho National Laboratory shared with the Senate in 2018:[60]

> "**A mature, tested and validated technology** has been developed and represents one potential solution to protect HV and EHV power transformers from the threat of both GMD's and EMP's...the EMP hardened transformer Neutral Blocking Device (NBD)...marketed as **SolidGround®**."

SolidGround®, produced by **EMPRIMUS**,[61] simply attaches to the neutral ground cable of a transformer, blocking GIC at the point of entry before it enters the grid.

It is a closed system (no tampering with existing AC controls) and is installed on the neutral ground cable of HV transformers. No customer load flows through the device. When quasi-direct current from a GMD or an E3 HEMP event attempts to enter from the earth through the neutral grounding connection of the transformer, the SolidGround® device automatically interrupts its path, eliminating the DC bias that causes half-cycle core saturation.

Simple connection to transformers

This prevention of half-cycle saturation **removes the heating, VAR consumption and harmonic effects**

[60] Op. Cit., Statement of Scott A. McBride, U.S. Senate, 2018 https://www.hsgac.senate.gov/wp-content/uploads/imo/media/doc/Testimony-McBride-2018-09-13.pdf
[61] EMPRIMUS, homepage, "About Us" https://www.emprimus.com/

that otherwise compromise transformer performance and grid stability during a GIC event. Importantly, the device accomplishes this protection without interfering with the transformer's normal AC ground and performance or its ability to safely handle fault currents.

This device has undergone extensive research and testing by academia through the University of Manitoba[62], by the government through the Department of Defense's (DoDs) Defense Threat Reduction Agency (DTRA), the Idaho National Laboratory (INL),[63] and the Oak Ridge National Laboratory (ORNL).[64]

SolidGround® was also purchased, installed and validated by the Department of Energy (DOE) per President Obama's Executive Order 13744 under Contract no. 89503421PWA001210, through public and privately owned utilities such as American Transmission Company (ATC), the Western Area Power Administration (WAPA), the Tennessee Valley Authority (TVA), and even through the utility industry's Electric Power Research Institute (EPRI), which has studied SolidGround® extensively.[65]

With over 10 years of operation history on the power grid at the 345kV level and above, the technology has demonstrated continuous operational reliability with zero maintenance-intensive failures and a 100% success rate blocking GIC automatically during GMD events. Unfortunately, the artificially low standard set by NERC provides no incentive to block GIC and protect the grid.

Meanwhile, outside of the United States, other countries do not rely on the NERC standard but instead on measured data and have tested SolidGround® and are beginning to install them on their nation's most critical transformers as they prepare for a 1:100-year solar event with a magnetic field strength of 4,000 nT/min.

Additionally, a Chinese entity has infringed upon the patents of the only proven viable neutral blocking device, the EMPRIMUS SolidGround® system, and is in production of these duplicate counterfeits, which are being deployed within China.

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[62] University of Manitoba Report: "Grid Impact of Neutral Blocking for GIC Protection" Prepared by Athula Rajapakse, 29 June 2013.
[63] SolidGround®, EMPRIMUS website, https://www.emprimus.com/solidground/
[64] Oak Ridge National Laboratory, Piesciorovsky, E., Tarditi, A., "Modeling the impact of GIC neutral blocking devices on distance protection relay operations for transmission lines", 2020. https://www.sciencedirect.com/science/article/abs/pii/S0378779619304547?via%3Dihub
[65] Research collection EMPRIMUS, https://www.emprimus.com/research

The Solution to GIC is Both Affordable & Bi-Partisan

The good news is that **protecting America's roughly 6,000 critical large power transformers identified "high-risk design" to GIC (the first to half-cycle saturate)** is affordable. Unlike massive, custom built, multi-million-dollar transformers, SolidGround® is not custom made but a standardized "one size fits all" device able to be produced on an assembly line. It costs about $500,000 and can be licensed to major transformer manufacturers to rapidly scale-up production and deployment across the United States. Nationwide deployment on the estimated 6,000 critical large power transformers would cost ≈ **$3–4 billion (one time cost)**—less than 0.5 percent of the 2021 Infrastructure Investment and Jobs Act

Employing SolidGround® to block GIC not only protects those critical transformers but also protects the rest of the grid *from* those transformers, which, if left vulnerable during extreme GMD or E3 HEMP events, will half-cycle saturate and take down the rest of the grid, damaging components with severe GIC-induced harmonics and VAR losses. This is what collapsed Quebec's electric grid in 1989 during a relatively minor GMD event (~ 2 V/km).

Again, we turn to **Scott McBride of Idaho National Laboratory**, who stated in testimony before the *U.S. Senate Homeland Security & Governmental Affairs Committee*, September 13, 2018:[66]

> *"...there must be a priority to protect the most critical large power transformers in place – my preliminary estimates are that **this would cost less than $4 billion** if we made it a priority to install NBDs at our most critical EHV substations."*

That cost estimate was validated by the nonprofit Foundation for Resilient Societies[67] and the independent analysis of ABB, Inc., which owns the largest collection of transformer designs in the US fleet.

Investing $4 billion to block GICs nationwide and defend some of the grid's most critical assets from HEMP would help deter our adversaries from using that method of attack. It would also save the American economy $15 billion in annual economic losses (2025 dollars) from routine solar weather. Based on this annual loss figure alone, the benefit-cost ratio of nationwide deployment makes it one of the most cost-effective resilience investments available in the energy sector.

Deploying the solution would also protect against large GMD events, which we cannot deter and are statistically certain to impact Earth in the future. In 2013, Lloyd's of London estimated the economic cost of a large "Carrington-class" solar storm (which occurred in 1859) on the North American grid today at between $0.6 and $2.6 trillion based solely on the value of lost load.[68]

Finally, the bipartisan appeal of this solution is worth emphasizing. The protection of critical grid infrastructure from GIC-induced failure is not a partisan issue; it aligns equally with national security imperatives, economic stability, and public safety. This bipartisan potential is reflected in prior executive actions. As noted previously, President Obama's Executive Order 13744[69] addressed space weather

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[66] Op. Cit., Statement of Scott A. McBride, U.S. Senate, 2018. https://www.hsgac.senate.gov/wp-content/uploads/imo/media/doc/Testimony-McBride-2018-09-13.pdf

[67] "Estimating the Cost of Protecting the U.S. Electric Grid from Electromagnetic Pulse", Foundation for Resilient Societies, 2020. https://www.resilientsocieties.org/uploads/5/4/0/0/54008795/estimating_the_cost_of_protecting_the_u.s._electric_grid_from_electromagnetic_pulse.pdf p. 63.

[68] Op. Cit., Lloyd's, "Solar storm Risk to the North American Electric Grid", 2013. https://assets.lloyds.com/assets/pdf-solar-storm-risk-to-the-north-american-electric-grid/1/pdf-Solar-Storm-Risk-to-the-North-American-Electric-Grid.pdf

[69] "Coordinating Efforts To Prepare the Nation for Space Weather Events", Presidential Executive Order, 2016. https://www.federalregister.gov/documents/2016/10/18/2016-25290/coordinating-efforts-to-prepare-the-nation-for-space-weather-events

preparedness, while President Trump's Executive Order 13865[70] focused on national resilience to EMP threats. Both directives recognized the need to protect infrastructure from GIC effects, implicitly supporting the kind of technology SolidGround® represents.

Cost Recovery

Moreover, SolidGround® deployment could be authorized and supported under FERC's **"just and reasonable"** standard for cost recovery,[71] allowing regulated utilities to recover investment costs through rate structures. This regulatory pathway removes one of the primary excuses for inaction – that utilities cannot justify the expenditure without guaranteed cost recovery – by giving them a clear and approved mechanism to finance the upgrades.

The conclusion is inescapable: SolidGround® is a mature, tested, and economically viable solution that can be scaled quickly and neutralizes the shared threats from GMD and E3 HEMP scenarios. It does so at a fraction of the potential economic and societal cost of inaction, without introducing operational trade-offs or vulnerabilities. **The barrier is not technical. The barrier is the willingness of policymakers and regulators to mandate widespread adoption of this technology before the next inevitable GMD or HEMP event tests the resilience of the U.S. grid.**

What America Must Do – Act Now

At present, the most powerful tool to protect our grid is not just a device, or a standard, but leadership.

It is leadership that is needed to overcome the decades of regulatory lethargy and industry lobbying that have slowed, deflected, or diluted serious mitigation measures to protect our grid from the GIC threat.

The responsibility for action now rests squarely on national and state-level leaders who have been elected by the people or appointed by their executives to serve the public interest. Below are steps that these leaders can take to rapidly protect the American people:

U.S. Federal Government

   1. DOE issues an Emergency Order to Identify GIC-Vulnerable Transformers: DOE should use the authorities granted it under Section 202(c) of the Federal Power Act (16 U.S.C. § 824a(c)), the energy emergency declared in EO 14156 (January 20, 2025), and the direction to use 202(c) authorities provided in EO 14262 (April 8, 2025) to require all ISOs/RTOs to conduct a thorough survey of all GIC-vulnerable electric transformers.

   The survey would identify those that must be protected against GICs from both GMD and E3 HEMP by using credible GIC scenarios for a 100-year solar storm and E3 waveforms associated with the recently updated international IEC standard (IEC 61000-2-9, Edition 2.0 2025-05), using the standard waveform in Figure A.5, modeling a peak magnetic field strength of 20,000 nT and corresponding electric field of 85 V/km. The emergency order should direct the results of the survey to be submitted within 180

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[70] "Coordinating National Resilience to Electromagnetic Pulses", Presidential Executive Order, 2019. https://www.federalregister.gov/documents/2019/03/29/2019-06325/coordinating-national-resilience-to-electromagnetic-pulses

[71] The Brattle Group, "The Zone of Reasonableness and Long Term Power Contracts", 2007. https://www.brattle.com/wp-content/uploads/2017/10/6321_zone_of_reasonableness_wp_fox-penner_wharton_mar_14_2007.pdf

days. The order should then be extended in 6-month increments until the nation produces and deploys the sufficient number of SolidGround® Capacitive Neutral-Blocking Devices to protect the electric grid from GIC.

<p style="text-align:center;">**[See Appendix III – Proposed Secretary of Energy Emergency Order on GIC Protection]**</p>

2. DOE Deploys SolidGround® Capacitive Neutral-Blocking Devices: DOE should start with federally owned portions of the U.S. electric grid such as the Tennessee Valley Authority (TVA), Bonneville Power Administration (BPA), Western Area Power Administration (WAPA), Southeastern Power Administration (SEPA), Southwestern Power Administration (SWPA), Alaska Power Administration (APA).

3. DOE Integrates GIC Mitigation into DOE's Reserve-Margin Methodology: Section 3(b) of EO 14262 directs DOE to develop a "uniform methodology for analyzing current and anticipated reserve margins." That methodology must consider not only fuel availability and generation dispatch but also the risk of generation loss from geomagnetic disturbances and HEMP E3 events.

Current planning models assume that generation capacity is lost only through mechanical or fuel outages. In reality, a single severe GMD could simultaneously disable hundreds of transformers, erasing gigawatts of reserve margin nationwide within minutes.

Therefore, DOE should:

A. **Mandate GIC-inclusive Reserve-Margin Assessment** for all regions regulated by FERC, using credible GIC scenarios for a 100-year solar storm and E3 waveforms associated with the recently updated international IEC standard (IEC 61000-2-9, Edition 2.0 2025-05)

2. **Identify At-Risk Regions** where modeled reserve margins fall below acceptable thresholds under the same credible GIC scenarios.

3. **Direct Priority Deployment** of SolidGround® capacitive neutral-blocking devices in those regions using TFP/GRIP funding.

4. **Publish a National GIC Hazard Map** analogous to FEMA's flood-risk maps to guide state and utility investment.

Incorporating GIC risk into DOE's reserve-margin model fulfills the Executive Order's mandate to use "all available generation resources" and ensures that the Nation's emergency energy analysis is grounded in physics rather than optimism.

<h2 style="text-align:center; color:#8b0000;">State Governments</h2>

The historical record of federal inaction does not prevent states from leading. Governors, working through their state energy offices and Public Utility Commissions (PUCs), already possess the authority to require investor-owned utilities (IOUs) to submit resilience readiness plans. They can direct infrastructure investment toward prioritized substation upgrades, encourage projects for GIC mitigation within existing rate structures, and support the deployment of SolidGround® in strategic locations.

State regulators can also leverage their rate-setting authority to incentivize prudent protective actions and can coordinate regional procurement of mitigation equipment to achieve economies of scale. Precedent exists: several states have already mandated grid protection measures in response to cybersecurity threats and wildfire risks.

In the wake of Winter Storm Uri, state leaders in Texas rapidly established an effective and enforceable standard for cold-weather protection much faster than FERC/NERC would have ever done – proving that state action can be effective and also supporting the concept that ERCOT should remain independent.[72]

In August 2025, the influential and bipartisan National Conference of State Legislators (NCSL)[73] passed a resolution urging swift action to protect our nation's electrical grid from solar geomagnetic disturbances (GMDs) and high-altitude electromagnetic pulse (HEMP).

New Hampshire State Representative Doug Thomas (R) sponsored the resolution, co-authored by Representatives JD Bernardy (R) and Rita Mattson (R). It passed unanimously after the legislators were informed that both President Obama and President Trump had written executive orders to address these threats, but that little had been done to actually harden the electric grid.

The full text of the resolution reads as follows:[74]

> *"Electromagnetic Pulses and Solar Flares (Resolution)"*
>
> *"NOW, THEREFORE, BE IT RESOLVED, that the National Conference of State Legislatures urges members of Congress and the President of the United States to initiate and coordinate efforts with state governments and the electric power sector to implement plans and preparation for the protection of electric power generation, transmission and distribution assets from EMPs and geomagnetic disturbances (solar flares); **first addressing those sectors most vulnerable and with the longest lead times for repair**, and then by using a risk based assessment approach to harden the remainder of nation's electric production, transmission and distribution systems for resilience against, and recovery from, all types of malicious or naturally occurring events that could adversely impact the electric power grid."* [Bold emphasis added.]

The resolution's approach of first addressing sectors that are the "most vulnerable and with the longest lead times for repair" is a wise one. It echoes the recommendations of leading HEMP/GMD experts and their concerns about assets with extremely long lead times, particularly transformers.

Therefore, the next logical step is for Governors, through executive action, or state legislatures through legislative action, to direct their utilities to survey all their transformers to vulnerability to GIC to determine how many need to be protected by SolidGround®.[75]

[Appendix IV includes robust model language for such legislative action.]

[Appendix V includes a condensed form of this model language developed by NH lawmakers.]

Due to the interconnected nature of the electric grid, these surveys will necessarily be conducted regionally within the Regional Transmission Operators (RTOs) and Independent System Operators (ISOs) that operate the grid. It would therefore be prudent for state leaders to work with the leaders of these RTOs and ISOs and with the leaders of the states they border. Once state leaders understand the scope of protection needed, they can create incentives and penalties for the electric utility industry to protect their assets by installing SolidGround® on vulnerable transformers. History demonstrates that the electric utility industry will lobby heavily in opposition to such requirements. Rate recovery is thus imperative so

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[72] https://centerforsecuritypolicy.org/5-reasons-why-a-federal-takeover-of-texas-electric-grid-will-hurt-resilience/
[73] National Conference of State Legislatures webpage, "About Us". https://www.ncsl.org/about-us
[74] https://nationalinterest.org/blog/energy-world/national-conference-of-state-legislators-urges-grid-protection-from-solar-weather-emps
[75] For assistance, state legislators should visit: https://centerforsecuritypolicy.org/center-for-security-policy-state-education-and-outreach-initiatives/

that the investments made in protecting the grid are shouldered by the people – who too must understand the criticality in protecting the grid from GICs.

Local Power: Civil Society and Citizen Pressure

Top-down policy from either the federal or state level will not succeed without bottom-up demand. Citizens, until now, have largely been disengaged from the technical and policy discussions surrounding grid resilience. That will change the moment electricity demand outstrips generation capacity or prolonged outages make the criticality of electricity "real" in daily life. The problem is that at that point, it is too late.

Proactive citizen action is therefore critical. Residential consumers should contact their governors and PUCs to demand protective measures, write directly to their utilities requesting transformer hardening, raise the profile of grid resilience in local media and community forums, and press local political candidates to take clear positions on the issue. The American public is not powerless, it is merely under-informed, and that is a problem that can be fixed.

Our Secure the Grid Coalition is consistently providing resources to educate the public and have been honored to work with documentary film producer David Tice on his production of the award-winning documentary "*Grid Down, Power Up*." Narrated by Hollywood celebrity Dennis Quaid, the film contributed to the success of Texas passing historic grid-protection legislation for its independent ERCOT grid, helping conclude ten-year legislative effort.

Grid Down, Power Up can be immediately viewed at: https://watch.salemnow.com/searchs?q=grid%2520down

Building a Network of Resilient Communities

Ultimately, the American people must become much better prepared for blackouts and more resilient at the community level. Our Center for Security Policy has produced a series of reports to encourage community leaders to take measures to increase resilience and bring back civil defense (*pictured and linked on the following page*).

We are also available to provide threat briefings to local elected and appointed officials and invite them to join our "Resilient Communities Network."

More information on the Center for Security Policy's community outreach can be found here:

https://centerforsecuritypolicy.org/elected-officials-emergency-manager-briefings/

Center for Security Policy Reports Encouraging Community Resilience

As Russia/Ukraine Situation Raises Specter Of Cyberwar, How Can We Be Better Prepared Here At Home?

BY TOMMY WALLER

FEBRUARY 2022

https://centerforsecuritypolicy.org/as-russia-ukraine-situation-raises-specter-of-cyberwar-how-can-we-be-better-prepared-here-at-home/

Bring Back Civil Defense

BY KYLE SHIDELER AND TOMMY WALLER

MARCH 2022

https://centerforsecuritypolicy.org/report-bring-back-civil-defense/

FOOD SECURITY IS NATIONAL SECURITY

BY TOMMY WALLER
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NOVEMBER 2022

https://centerforsecuritypolicy.org/report-food-security-is-national-security/

A Model of Resilience:
Waldo County Maine's Off-Grid Emergency Operations Center

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SEPTEMBER 2023

https://centerforsecuritypolicy.org/a-model-of-resilience-waldo-county-maines-off-grid-emergency-operations-center/

Appendix I – NERC/FERC Rulemaking Puts America – And the World – At Risk

The slow pace of rulemaking within the Federal Energy Regulatory Commission (FERC) and its designated Electric Reliability Organization (ERO), the North American Electric Reliability Corporation (NERC), has repeatedly left the United States vulnerable to known and well-documented threats. While these bodies have statutory authority to address reliability risks to the bulk power system, the historical record shows that the process of developing, approving, and implementing new standards can take years. This is true even when the threat is urgent, the technical solutions are well understood, and the potential consequences of inaction are catastrophic.

Because other modern societies with electric grids look to the United States and NERC for the development of their own reliability and security standards, NERC can either enhance or undermine the resilience of grid infrastructure worldwide. For solar weather, which poses a threat to the entire globe, the lives of more than America's 330 million citizens are at risk if other nations choose not to protect their grids against GIC by following NERC's lead.

Thus, it is worth reflecting on the NERC/FERC rulemaking processes surrounding a few notable past examples:

The 2003 Northeast Blackout: Congressional Action and Regulatory Bottleneck

The August 14, 2003, Northeast blackout, which left over 50 million people without power across eight U.S. states and Ontario, was triggered in part by overgrown vegetation contacting 345 kV transmission lines.[76] In response, Congress passed the Energy Policy Act of 2005 (EPAct 2005), expanding the Federal Energy Regulatory Commission's (FERC) authority under Section 215 of the Federal Power Act to certify an Electric Reliability Organization (ERO) responsible for developing and enforcing mandatory reliability standards for the bulk power system.[77] On July 20, 2006, FERC designated the pre-existing North American Electric Reliability Corporation (NERC), originally a voluntary trade association formed in 1968, as the ERO.

Vegetation management emerged as an immediate priority for the new FERC-NERC framework, given its direct role in the 2003 cascade. **Despite this urgency, it took approximately 9.5 years** from the 2003 blackout—until FERC's approval of Reliability Standard FAC-003-2 in Order No. 777 on March 21, 2013—**for a fully enforceable standard to be finalized**. This standard introduced minimum vegetation clearance distances based on the "Gallet equation", annual inspections, and expanded applicability to critical lower-voltage lines, addressing deficiencies identified in earlier versions.[78]

This protracted timeline reflects the deliberate, industry-driven nature of NERC's ANSI-accredited standards development process, which requires multiple rounds of drafting, public comment, balloting, and FERC review to ensure technical rigor and industry consensus. While it is claimed that voluntary

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[76] U.S.-Canada Power System Outage Task Force, "Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations", 2004. https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/BlackoutFinal-Web.pdf

[77] FERC Ruling: "Rules Concerning Certification of the Electric Reliability Organization; and Procedures for the Establishment, Approval, and Enforcement of Electric Reliability Standards", 2006. https://www.federalregister.gov/documents/2006/02/17/06-1227/rules-concerning-certification-of-the-electric-reliability-organization-and-procedures-for-the

[78] FERC Ruling: "Revisions to Reliability Standard for Transmission Vegetation Management", 2013. https://www.federalregister.gov/documents/2013/03/28/2013-07113/revisions-to-reliability-standard-for-transmission-vegetation-management

efforts reduced vegetation-related outages by over 50% in the interim, the delay in mandatory enforcement left persistent reliability gaps, contributing to events like the 2011 Southwest blackout.[79]

The vegetation management case exemplifies the trade-offs in our industry-driven regulatory construct which facilitates compliance. Such accommodation hinders rapid response to known vulnerabilities in an aging and stressed grid.

Regulatory Lethargy Has Costs

Past examples illustrate the danger of these delays. One FERC directive to NERC to develop standards for physical security, Order No. 802, came in the wake of the April 2013 Metcalf substation attack, in which unknown attackers caused over $15 million in damage to a critical transformer yard serving Silicon Valley. Despite the clear demonstration that a small, coordinated team could inflict serious damage on critical grid infrastructure, the resulting NERC standard (CIP-014) took nearly two years to finalize. Moreover, its final form allowed industry discretion in identifying which facilities were "critical" and thus subject to protection, resulting in many vulnerable assets being excluded from any mandated security measures.[80]

The timeline for GMD protection standards is even more troubling. FERC first directed NERC to create geomagnetic disturbance (GMD) reliability standards in 2013 under Order No. 779,[81] which launched a two-stage rulemaking process to address both operational and planning vulnerabilities. The first planning standard, TPL 007-1, was not approved until September 2016 through order number 830,[82] and even that approval included directives for further modification to improve model validation, geomagnetic latitude scaling, and data collection. Implementation was phased over five years under NERC's 2014 implementation plan,[83] meaning protections would come online only gradually. Subsequent revisions - TPL-007-2 (2018),[84] TPL-007-3 (2019),[85] and TPL-007-4 (2020)[86] - each took years to develop and phase in, with new compliance dates extending still further.

Even today, regulators acknowledge that the GMD standard continues to fall short of protecting against historically credible storm intensities, illustrating how a single FERC directive can evolve through nearly a decade of slow, iterative bureaucratic process before delivering a standard that experts have long questioned as inadequate, because its chosen benchmark event, which forms the analytical foundation of the entire GMD standard, is grounded in fallacy. [See above section "NRC Reliance on a Flawed NERC Standard"] Hence, the current version still falls short of providing adequate protection against historically credible events.

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[79] 2018 Conference 2018 IEEE Power & Energy Society General Meeting (PESGM), "Vegetation-Related Outages on Transmission Lines in North America", 2018. https://www.researchgate.net/publication/329898451_Vegetation-Related_Outages_on_Transmission_Lines_in_North_America
[80] NERC, CIP-014 Report – Physical Security Protection for High Impact Control Centers
Docket No. RM15-14, 2017. https://www.balch.com/-/media/erl-blog/cip014-high-impact-control-center-report.pdf
[81] FERC, Reliability Standard for Geomagnetic Disturbance Operations, RM14-1-000, 2014. https://www.ferc.gov/sites/default/files/2020-05/E-3_19.pdf?
[82] FERC, Order No. 830, Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events, RM15-11-000, 2016. https://www.ferc.gov/sites/default/files/2020-04/E-4_2.pdf
[83] NERC, Implementation Plan: Project 2013-03 Geomagnetic Disturbance Mitigation, 2014. https://www.nerc.com/globalassets/standards/projects/2013-03/tpl_007_1_implementation_plan_20141205_clean.pdf
[84] FERC, Geomagnetic Disturbance Reliability Standard, RM18-8-000, 2018. https://www.ferc.gov/sites/default/files/2020-12/RM18-8-000.pdf
[85] NERC, Implementation Plan: Project 2019-01 Modifications to TPL-007-3, 2019. https://www.nerc.com/globalassets/standards/reliability-standards/tpl/draft-tpl-007-4-implementation-plan_final-ballot_qr.pdf
[86] NERC, TPL-007-4 – Transmission System Planned Performance for Geomagnetic Disturbance Events, https://www.nerc.com/globalassets/standards/reliability-standards/tpl/tpl-007-4.pdf

This protracted pace of rulemaking is not simply a function of procedural complexity; it is often the result of deliberate industry lobbying to limit the scope and cost of new requirements. NERC's standards development process is industry-led, with utility representatives holding substantial influence over drafting teams and balloting bodies. When proposed measures threaten to impose significant costs, such as the installation of GIC-blocking devices on critical transformers, industry stakeholders can and do use procedural mechanisms to delay, dilute, or derail the standard.

The Costs are the Placing of Our Society in Harm's Way

The result is a pattern in which years pass between the identification of a serious vulnerability and the implementation of even partial protection. During this time, the grid remains exposed, and adversaries are given a clear window of opportunity, and they know it. The slow-motion approach to risk mitigation is especially dangerous for high-impact, low-frequency events like severe GMDs and HEMP attacks, where the absence of recent precedents is wrongly interpreted as justification for delay.

This institutional inertia is compounded by the absence of binding statutory deadlines for standard development. While FERC can order NERC to create or revise a standard, it rarely specifies aggressive timelines, and NERC's internal processes default to multi-year development cycles. The end result is that critical protections arrive, if at all, long after the window for timely action has closed.

The consequences of such delays are not theoretical. Had a Carrington-class solar storm struck during the decade-long gap between the 2012 near-miss CME and the present, the grid would have collapsed and – depending on the severity of GIC-induced transformer damages – it may still not have been restored. In national security terms, this is equivalent to acknowledging a known vulnerability in missile defense and then taking a decade to decide whether to employ a countermeasure, all while adversaries actively prepare to exploit the gap.

Without reform of the rulemaking process—whether through statutory deadlines, streamlined procedures, or the imposition of interim protective measures—the cycle of delay will continue. And each year that passes without decisive action is another year in which the United States gambles with the survival of its most critical of critical infrastructures.

Appendix II - Myths Vs Facts on GICs from GMD/HEMP

Decades of inaction on GMD/HEMP threat mitigation stem not only from bureaucratic delays and budget constraints, but also from a set of persistent myths that have seeped into policymaking and utility culture. Sometimes the myths are purposely inserted into the policy debate by lobbying organizations seeking to downplay the threats to the grid or to bolster the notion that they are addressing these threats.

An example of this that pertains to GMD/HEMP occurred in February 2015 with the Edison Electric Institute (EEI) publishing a white paper titled "Electromagnetic Pulses: Myths vs. Facts."[87] In May 2015, our Secure the Grid Coalition published a rebuttal[88] to this document, which was subsequently scrubbed from the internet.

Similarly, in April 2019, the industry-funded Electric Power Research Institute (EPRI) published a report titled: "High-Altitude Electromagnetic Pulse and the Bulk Power System: Potential Impacts and Mitigation Strategies." <u>This report vastly understated the gravity of the EMP threat</u>, to the point that the U.S. Air Force Electromagnetic Defense Task Force (EDTF) was compelled to author a counterpoint paper published by the Air Force's "Over the Horizons" online journal[89].
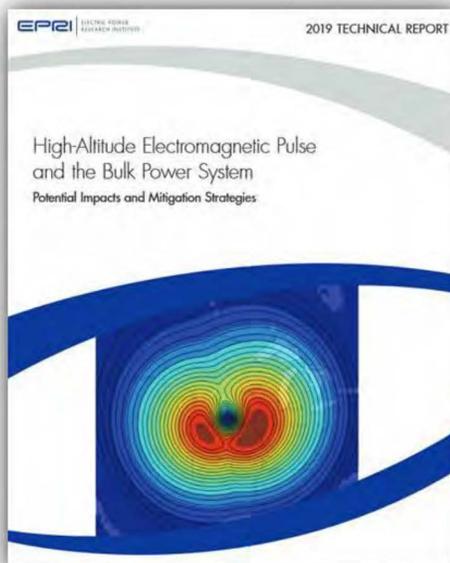
That USAF EDTF article plainly stated the truth:

> **"If US Government policymakers rely upon the methodology and conclusions of the EPRI report, effective high-altitude EMP protections will not be implemented, jeopardizing security of the US electric grid and other interdependent infrastructures**."

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[87] https://securethegrid.com/wp-content/uploads/2019/03/EEI-Misinformation-Electromagnetic-Pulses-EMPs-Myths-vs.-Facts.pdf
[88] https://securethegrid.com/wp-content/uploads/2025/11/STG-RebuttalToEEII-Misinformation.pdf
[89] https://othjournal.com/2019/08/27/electromagnetic-pulse-threats-to-americas-electric-grid-counterpoints-to-electric-power-research-institute-positions/

Unfortunately, these myths are repeated in public statements, testimony, and even regulatory filings, often without scrutiny. These myths create a dangerously false sense of security and undermine the urgency for adopting proven protective measures. Confronting these misconceptions directly, with documented facts, is essential to clearing the path for prudent, cost-effective protection of the grid. Below are 14 important myths related to the GIC threat to the grid and the subsequent facts to correct the record.

Myth #1 — "Transformers are immune to GIC damage."

Fact. U.S. large power transformers—whose average age today is roughly **38–40 years**—are **not** immune to geomagnetically induced currents (GICs). This myth is typically based on the assertion, advanced by some in the electricity complex, that 80% of the US high voltage transformer fleet is "resistant" to GIC effects. The physics are straightforward: quasi-DC bias drives half-cycle saturation, which in turn produces harmonics, hot spot overheating, core stress, and progressive insulation damage; in severe cases this cascade ends in catastrophic failure. These effects are not speculative. **National laboratory reports**,[90] **utility testbeds**[91] and **transformer manufacturer disclosures**[92] have documented them for decades. Aging magnifies the risk because cellulose insulation and dielectric oil degrade over time, narrowing the thermal and electrical margins within which a transformer can ride through even moderate GIC exposure.[93] The way you operate a transformer can also increase its aging. Today we are placing higher power demands on our transformers.

Myth #2 — "NERC's TPL-007 proves the system is secure."

Fact. The NERC TPL-007 standard ignores NERC's own committee of 8 respected space weather scientists who estimated a reference storm in February 2013, the "preliminary results" were determined to be a maximum electric field strength of 30-40 V/km.

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[90] Los Alamos National Laboratory, Review of the GMD Benchmark Event in TPL-007-1, 2015. https://www.energy.gov/oe/articles/review-gmd-benchmark-event-tpl-007-1

[91] Hydro-Québec, Montréal, Québec, "GMD Impacts on Hydro-Québec system", 2023. https://www.ipstconf.org/papers/Proc_IPST2023/23IPST017.pdf

[92] ABB Power Transformers, "Effect of GIC on Power Transformers & Power Systems" https://www.pes-psrc.org/kb/report/1020.pdf

[93] University of Quebec at Chicoutimi and Hydro Quebec Research Institute, "Degradation Mechanisms of Cellulose-Based Transformer Insulation: The Role of Dissolved Gases and Macromolecular Characterisation", 2025. https://www.mdpi.com/2673-6209/5/2/20

Slide 54 from NERC GMD Task Force presentation

See presentation slides of "GMD Task Force Phase 2 Ken Donohoo, Task Force Chairman, In-Person Meeting, February 25-27, 2013", p. 52 and other relevant material available at http://www.nerc.com/docs/pc/gmdtf/MeetingSlides_25Feb_final.pdf . Space weather scientists on the "Current Science Team" at the time of the 30-40 V/km geoelectric filed estimate included A. Pulkkinen (NASA/CUA), W. Murtagh (NOAA), C. Balch (NOAA), J. Gannon (USGS), D. Boteler (NRCan), R. Pirjola (NRCan), D. Baker (U. of Colorado), and A. Thomson (BGS/EURISGIC).

See "Response to NERC Request for Comments on Geomagnetic Disturbance Planning Application Guide," Resilient Societies, Comments to NERC GMD Task Force, August 9, 2013, filed as a record of standard-setting.[94]

Instead the **NERC TPL-007** standard rests on **low historical benchmarks** of a selected period of particularly low solar activity, and the geophysical makeup of Europe which differs markedly from the geophysical characteristics common to most of North America.[95] The standard also excludes the largest known storms, including **1921** and **1859**.[96] It also lets utilities **self-select** key modeling inputs, such as **assumed ground conductivity,** that strongly influence exposure calculations.[97] The combined effect is to weaken the floor that "minimum" reliability thresholds were meant to establish. The chosen benchmark

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[94] http://www.resilientsocieties.org/uploads/5/4/0/0/54008795/comments_20130809_gmd_planning_application_guide.pdf
[95] Op. Cit., Los Alamos National Laboratory, Review of the GMD Benchmark Event in TPL-007-1, 2015. https://www.energy.gov/oe/articles/review-gmd-benchmark-event-tpl-007-1
[96] NERC, Level 2 Appeal Foundation for Resilient Societies, Inc. TPL-007-1 - Transmission System Planned Performance for Geomagnetic Disturbance Events https://www.nerc.com/globalassets/standards/projects/2013-03/2013-03_gmd_level_2_appeal_foundation_for_resilient_societies_tpl-007-1_05182015.pdf
[97] Ibid.

event, 8 volts per kilometer (over Quebec) and scaled down to 4 V/km (northern U.S.), 2 V/km (center of the U.S.) and 0.8 V/km (southern U.S.),[98] does not represent a credible worst-case storm for North America. This **standard is set at a level that avoids the need to install hardware to protect the power grid.** A standard built on under-representative data and flexible assumptions **cannot** serve as proof of system security against severe GMDs.

Myth #3 — "If GICs were a real danger, we'd see more blackouts."

Fact. Historical records and modern near misses refute this contention. We have not experienced a large GMD direct hit since the modern grid was developed.
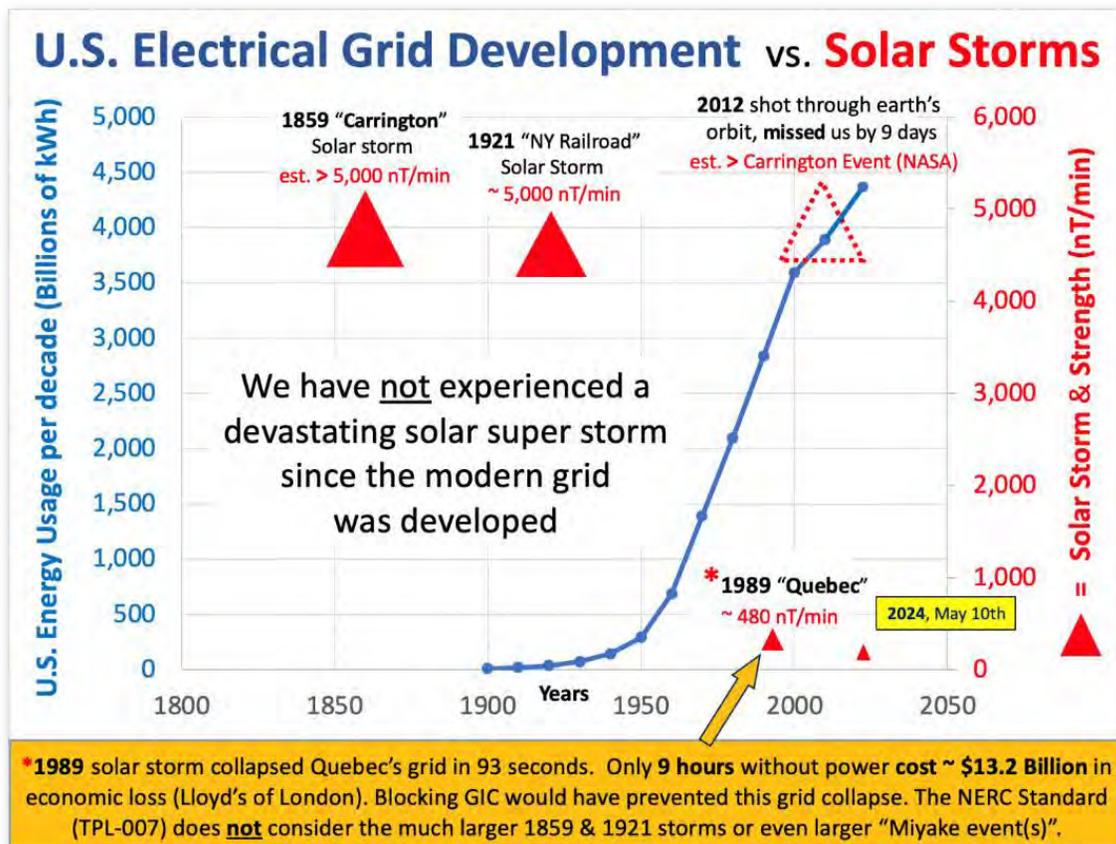
The 1859 "Carrington Event" and the 1921 "NY Railroad" Solar Storm are proof that extreme space weather has occurred in the past (prior to the development of our bulk power grid) and are statistically certain to occur again. NASA cites the estimates of the probability of a Carrington class CME hitting Earth at 12% per decade.[99] The absence of clearly labeled "GIC blackouts" is not evidence of safety; it reflects **misattribution** and **under-monitoring**. In most substations there is **no real-time GIC monitoring**, so operators often assign resulting disturbances to other causes. Moreover, GIC damage can be **cumulative**: thermal stress and insulation degradation may set the stage for failures **years** later, long

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[98] NERC, Benchmark Geomagnetic Disturbance Event Description Project 2013-03 GMD Mitigation Standard Drafting Team (corrected)", 2014. https://www.nerc.com/globalassets/standards/projects/2013-03/benchmark_gmd_event_june12_redline_corrected.pdf
[99] Riley, P., "On the probability of occurrence of extreme space weather events", 2012. https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2011SW000734

after the initiating events.[100] Moreover, near-misses matter. As the Earth orbits around the sun, the sun rotates on its own axis shooting off large solar flares with coronal mass ejections ("CMEs") through the Earth's orbit. If the Earth happens to be in the line-of-sight of one of these large CMEs, the results will be catastrophic. **We are in essence playing Russian roulette with the sun**. The **2012 solar superstorm** that **missed Earth by nine days** demonstrates how unprepared the grid remains for a Carrington-class strike. Per NASA that 2012 event was "in all respects at least the size of Carrington."[101] Recall that Lloyd's of London estimated in 2013 that if a Carrington sized event were to occur, it would cost the U.S. economy between $0.6 to 2.6 trillion based on value of lost load, not including catastrophic loss of life and equipment damage.

As for HEMP E3 threats, adversary nations already possess both the weapons and delivery systems capable of executing such an attack. As mentioned earlier, **in 1962 the Soviet's achieved 66 V/km (many times larger than the "Carrington" event)**. China's manifesto "How to Defeat a Superior Adversary" was developed following the first Gulf War and cites initiating a "Black Out" war by completely turning off the adversary's power via EMP. Three other nation states have adopted this same plan – Russian, North Korea and Iran. These are not remote possibilities; they are predictable risks within the foreseeable future.

Myth #4 — "Operational procedures alone can safeguard the grid during GMD or EMP events."

Fact. Operating procedures do not block GIC from entering an operating grid. There is **no practical way** to detect and **preemptively** de-energize the grid in time to prevent damage in an **E3 HEMP** event, which unfolds in **seconds**. SolidGround® automatically blocks GIC induced by E3 HEMP or GMD when detected in the neutral of the transformer. Even for GMDs with timely warnings from NOAA's Space Weather Prediction Center, **utilities lack documented policies** to voluntarily take systems offline—contractual obligations and liability concerns make such actions unrealistic. Capacitors installed in the neutral that automatically **block GIC in the Earth from entering into transformers** through the ground connected neutral wires is therefore essential.

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[100] Op. Cit., "Geomagnetic Disturbances (GMD) Impacts on Protection Systems", https://www.pes-psrc.org/kb/report/022.pdf
[101] NASA Science Editorial Team, "Near Miss: The Solar Superstorm of July 2012", 2014. https://science.nasa.gov/science-research/planetary-science/23jul_superstorm/

Operating Procedures are not sufficient

Operating Procedures

- Do **not** block **GIC (DC Current)** from entering an operating grid

- Do **not** prevent half-cycle saturation, harmonics or wear on transformers

- **Procedures** to decrease load on vulnerable transformers **increase risk** to **HV Breakers**

- Susceptible to human error - Require minutes to hours after a GMD warning (**no warning** prior to **EMP**)

- **VAR Supply** is limited and a dangerous approach during severe events - **exposes critical grid components to severe GIC & harmonics over longer duration**

- Low-level GIC events currently cause **$Billion(s) in economic loss each year**

Vs.

SolidGround® Neutral Blocker

- ✓ Automatically **blocks GIC**, prevents half-cycle saturation, **prevents harmonics**

- ✓ Allows Grid Operators to maintain control of the grid w/ **reliable operation of HV Breakers** without GIC across them

- ✓ **Operates in milliseconds** when **GIC** or **E1** is detected. Not susceptible to human operational error or delays during event

- ✓ **Prevents voltage collapse (blackouts)** Decreases VAR consumption allowing utilities to operate through a large Carrington level event

- ✓ **Perfect track record** over many years blocking GIC from Low-level GMD events. **No unintended consequences** to grid

It is critical to block GIC from entering our AC power grid

Myth #5 — "GIC solutions are unproven or prohibitively expensive."

Fact. The **SolidGround®** capacitive neutral-blocking device has been **deployed** by **TVA**, **WAPA**, and **ATC** for **as long as 10+ years without failure** and without operational issues. It has passed **DTRA/INL** HEMP E3 validation and is considered **cost-effective**. The "prohibitively expensive argument collapses under basic cost-benefit analysis. Unmitigated GIC-related impacts are estimated at **$15 billion annually (approximate 2025 dollars)** due to low GIC induced harmonics injected into the grid by the most susceptible transformers on our power grid. Deploying "SolidGround" GIC blocking technology on 6,000 of the nation's most susceptible high voltage transformers to half-cycle saturation has a one-time cost of $4 billion (**less than one-third of one-percent of the $1.2 trillion Bipartisan Infrastructure Bill**), making mitigation a fraction of ongoing losses, paying for itself multiple times each year. In other words, this is not an untested technology or an extravagant expense; it is a straightforward and proven fix with a compelling economic case, alone, not considering the element of human suffering and death. In addition, SolidGround® can reduce or eliminate many complex and costly operating procedures (such as reducing load or spinning up generation and utilizing SVCs to supply VARs) in an attempt to reduce risk of thermal damage and blackouts related to GIC. Utilities can pre-emptively place SolidGround® units across their grid into "Blocking Mode" via SCADA whenever a GMD warning is issued by NOAA of an incoming event, or allow them to automatically block GIC whenever it is present. In the case of a surprise

E3 HEMP attack, SolidGround® detects both the E1 pulse and GIC automatically triggering into Blocking Mode.

Myth #6 – "A spare transformer program is the solution"

Relying on spare transformers as a solution is considered to be "the Great Experiment" and it's a dangerous one. Experts within DOE and the utility industry are uncertain whether we would be even able to plug in a large spare transformer in a widescale blackout scenario with societal chaos after a severe GMD or HEMP E3 attack. Plugging in a spare transformer requires a full crew and about a month of work in "blue sky conditions" with functioning communications and a functioning grid.

The most vulnerable transformers to GIC (first to half-cycle saturate and fail) are also the largest transformers (500kV-765kV and large GSUs and Converter transformers), they hold many 10,000s of gallons of oil that needs to be transported, heated and tested. Most of these large power transformers are custom made, and take up a very large area. ABB's RecX spare transformer program never attempted to make spares in the 500 kV size or above due to their incredible size. An enemy attacking the U.S. with HEMP E3 will never allow a spare unit to be plugged in, if successful, they will hit us again and knock out the spare. Severe GMD events can last for over a week which would delay any efforts to plug in a spare, even if one were to be available.

SolidGround® Neutral Blocking Device (NBD)

500 kV Transformer

A "spare transformer program" is <u>not</u> a solution

- This 500 kV transformer takes up almost a football field worth of space
- **These largest transformers** are the **most vulnerable to GIC** (because of their single-phase design) and will be <u>first to fail</u> in a large GMD/E3 event
- Spares are not a solution: 1st **EMP** attack knocks out the transformer, 2nd **EMP** attack knocks out the spare, if ... there is even a chance to plug it in

- **Lead time: 4-6yrs to order 1 transformer.** Most are custom made. If you order 1,000s of transformers, the lead time will be many decades.

- **Replacement Process: (Month +)** To replace a large transformer with a spare, they need to empty 10,000 – 60,000 gallons of bad transformer oil (too heavy to move with oil). **Then use a very large crane (lifting capability up to 400 tons) to move** damaged transformer out of place. **Find one of only about 30 "Schnabel" carts in existence in the U.S. capable of moving these extremely heavy transformers (while empty).** Use that cart to transport the spare transformer to the site, use the heavy lifting crane to move it into place. **Schedule many tanker trucks to fill up transformer with new transformer oil (10 to 60,000 gallons each).** Perform vacuum tests.

Myth #7 — "Neutral resistors are effective for GIC protection."

Fact. Neutral resistors do <u>not</u> prevent half-cycle saturation, **harmonics or reactive power losses** that result from GIC - disqualifying them as a protection option.

"The half-cycle saturation of the great number of large power transformers on a power system is the source of nearly all operating and equipment problems caused by GIC's during magnetic storms..." - EPRI TR-100450, 1992

"The flow of GIC in transformers is the root cause of all power system problems, as the GIC causes half-cycle saturation to occur in the exposed transformers" – ORNL, Meta-319, 2010, p1-20.

Resistors reduce GIC (and AC)...they **do <u>not</u> block GIC**. It takes very little GIC to begin saturating many of the largest HV transformers (as low as **2 to 5 Amps GIC/phase**.)

*"**Only a few amps of GIC** can result an amplification of impacts in the operation of AC current flows in the transformer."* ORNL, Meta-319, 2010, p1-20

Even reducing GIC by 60-80% utilizing resistors cannot prevent catastrophic results during a large **GMD or E3 HEMP event which can cause 100s to 1000s of Amps GIC/phase**. Each transformer half-cycle saturating due to GIC is turned into a harmonic current generator (injecting harmonics into the grid, destroying components across the grid all the way to the load) and reactive power consumer (driving the power grid towards blackout).

Golden Rule in GIC mitigation: keep GIC <u>below 6 Amps</u> in the neutral (2 Amps/phase). This prevents the largest "high risk design" power transformers from half-cycle saturating and injecting GIC induced harmonics into the power grid. International utilities have gone to extreme lengths stacking large resistors in series with additional resistors in an attempt reduce GIC (or stray DC in the ground from HVDC operation) to below 6 Amps to prevent transformer harmonic generation. It is for this reason SolidGround® capacitive neutral blockers for over a decade have been set to begin blocking when GIC reaches 5 Amps in the neutral...just below the 6 Amp threshold. International utilities are now beginning to tear out their large resistors and install SolidGround® which simply blocks GIC bringing it down to zero. **Blocking GIC from entering these "high risk design" transformers** not only protects those critical transformers, it **protects the rest of the power grid and critical components *from* those transformers.**

Resistors installed in the neutral 100% of the time will increase wear on transformers continually stressing the neutral insulation off our aging transformer fleet during every power system event (faults, switching transients, inrush, sympathetic inrush, etc...).

By contrast, **capacitor-based neutral blockers**—exemplified by SolidGround®—maintain a solid metallic path to ground 99.9% of the time during normal operation and **automatically block GIC** only when present through a resistor in series with a capacitor, while preserving normal AC operation and ground-fault protection 100% of the time. Real-world data on the power grid at Idaho National Labs, American Transmission Company and DOE's project(s) installing and operating SolidGround® at Tennessee Valley Authority (TVA) and Western Area Power Administration (WAPA) show **no unintended consequences**, and technical references explain why blocking with capacitors, <u>not</u> resisting with resistors, is the correct engineering approach.

EPRI EL-3295, Project 1770-1, 1983;

*"A **capacitor in the neutral** of transformers was determined to be the **most effective and practical** blocking device." p.9-1*

*"The **most promising** system uses **neutral blocking capacitors**..." p.vi*

*"A **capacitor, installed in the neutral** of the transformer, was selected as the **most suitable** device for blocking GIC." p.S-2*

*"The basic requirement to block dc while providing a low ohmic ac path in the neutral suggests that **capacitors are a prime candidate** for consideration." p.3-2*

EPRI TR-100450, 1992;

*"...inserting blocking devices in neutral leads appears to be the **most logical and effective** means of preventing GIC flow... the use of ordinary **capacitors is the best option** for a GIC neutral blocking device."*

*"The **limited effectiveness of linear resistance** unless relatively high values of resistances are used, **and the other disadvantages** associated with their use, combine to make them a **less favorable choice for blocking or limiting GIC than capacitors**."*

"High-Altitude Electromagnetic Pulse and the Bulk Power System: Potential Impacts and Mitigation Strategies." EPRI, Palo Alto, CA: 2019. 3002014979:

*"...**capacitors** in the neutral...**effective** means of blocking the flow of GIC..."*

Myth #8—"Widespread application of neutral capacitors would bring risk of impedance changes and ferroresonance concerns on the network."

Fact. This was an **early concern regarding old blocking technology** developed in the 1980s and 90s which has been **specifically addressed with the development of SolidGround®.**

The University of Manitoba completed 6 detailed reports on capacitive neutral blocking devices ("NBDs") and concluded *"As expected, frequency scans show that neutral grounding capacitors has no impact on the positive sequence impedance frequency characteristics...at harmonic frequencies (f > 60 Hz), the impact of neutral grounding capacitors on the zero sequence impedance is negligible **when the grounding capacitance is larger than 1000 μF**."*

Oak Ridge National Laboratory analyzed capacitive neutral blocking devices ("NBDs") installed on the grid and their conclusions showed that *"**distance relays operate normally** in transmission lines with NBDs inserted, **if the neutral grounding capacitance is greater than 1,000 μF**"[102]*

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[102] Reference: Modeling the impact of GIC neutral blocking devices on distance protection relay operations for transmission lines, Electric Power Systems Research, Volume 180, March 2020, 106135

Old blocking technology utilized capacitors with very low capacitance (10 µF and 61 µF). SolidGround® utilizes **a resistor in series with a capacitor** bank of **high capacitance (1,289 µF)**.

SolidGround® is installed on various transformer designs at the 345 kV and 500 kV level and has been continuously operating on the power grid for over 10 years with **no negative effects to the power system**, no resetting of protection relays, no ferroresonance.

Myth #9   Blocking GIC from entering our power grid will create "Whack-a-Mole"

Whack-a-Mole is an assumption that if you block GIC in one location, it will cause GIC to be "re-directed" and spike everywhere else. Example: If you block 10 Amps GIC at one transformer, then 10 Amps GIC (or more) will be shifted somewhere else. In essence - we can't solve the GIC problem.

Fact. Over 10 years of GIC data refutes this assumption. To study this, **DOE under Executive Order 13744 purchased SolidGround® NBDs and installed them on the most GIC monitored grid in the U.S.** This has allowed DOE to monitor GIC levels across the grid in real time as NBDs operated during many GMD events (of various angles), and to record that data to see the impact of blocking GIC.

DOE Objectives:

- Assess the effectiveness of SolidGround® NBDs to block GIC
- Measure any GICs re-directed to other transformers
- Use data to validate modeling and correct inaccurate assumptions

90+ SolidGround® operations analyzed by DOE, EPRI and EMPRIMUS during many GIC events

Results are consistent:

- SolidGround® NBDs operating as designed, no negative effects to power system
- GIC in neutral of protected transformer drops to zero
- Re-directed GIC is minimal and local (**V = IR**)
- **Network GIC** (sum of all GIC monitored on the system) **decreases**

NBD Impact on Protected 500kV Transformer
NBD impact can only be measured _the instant_ the NBD changes the GIC circuit

Transformer Protected With SolidGround® NBD - Neutral GIC
SUNBURST and Utility 1-second Data

Data from DOE Projects under EO 13744

NBD Impact to Neighboring Substations
NBD impact can only be measured _the instant_ the NBD changes the GIC circuit

SolidGround® Neutral Blocking Device
Impact to Neighboring Sites at Operation
SUNBURST and Utility 1-second GIC Data

Data from DOE Projects under EO 13744

NBD Impact to Network GIC

NBD impact can only be measured <u>the instant</u> the NBD changes the GIC circuit

Total Network GIC Across All Monitored Sites At SolidGround® NBD Operation
SUNBURST and Utility 1-second GIC Data

2024-10-08, 05:00:13 UTC

Data from DOE Projects under EO 13744

DOE's data consistently shows that **blocking GIC** in the neutral of transformers **decreases Network GIC**. (i.e. GIC is <u>not</u> being re-directed everywhere else, grid resilience is improving). The more NBDs installed on the power grid, the more resilient the power grid becomes allowing the grid to operate through severe GIC events. **Modeling assumptions need to be updated to reflect the data.**

% of Transformers with SolidGround® NBDs	% Reduction of Total Network GIC	% Decrease in Reactive (VAR) Consumption
7%	13.7%	14.6%
14%	27.3%	29.3%
21%	41.0%	43.7%

Results derived from PowerWorld ™ modeling of the Wisconsin ATC Power Grid

E. "Re-directed" GIC is a concern today if we do <u>not</u> protect the power grid

GIC will always travel the path of least resistance. During a severe GMD or E3 HEMP event, **the instant high voltage circuit breakers are operated** (intentionally via utility operating procedures or unintentionally due to GIC induced harmonics or E1 HEMP) **the <u>GIC circuit is changed and </u>GIC will be re-directed across the grid** in an unplanned and chaotic manner.

It is important to note that **high voltage circuit breakers** attempting to open (intentionally or unintentionally) during a severe GIC event can be catastrophically destroyed as they require "zero crossings" and **are <u>not</u> designed to break GIC**.

Myth #10—"Allowing a severe GMD or E3 event to take the grid down, will save transformers from catastrophic damage."

Fact. Grid failure itself will catastrophically damage many transformers and other components across the grid. It is widely accepted that when the sun produces another geomagnetic disturbance larger than the NERC TPL-007 standard (i.e. "2012 CME near miss" which blasting off the back side of the sun, 1921 "Railroad Event", 1859 "Carrington event" and even larger "Miyake events") or there is a single E3 HEMP attack, our grid will go down very quickly due to severe levels of GIC induced harmonics.

On July 21st, 2016 DOE members held a meeting with various leading suppliers and utilities in the industry (DOD, INL, LANL, ABB, Siemens, Dominion, EMP Commission, EPRI, MITRE, STRATCOM, NATF...) to discuss our nations EMP Resilience Action Plan to identify specific actions "where DOE can help the most" to protect the power grid from EMP. A few important takeaways from that meeting:

- **Priority #1 – prevent grid failure**. GIC induced Harmonics from E3 and severe GMD will cause wide scale grid collapse in just 10's of seconds.
- Large scale load shedding is not possible. **Equipment is damaged in the shed/reconnect process due to switching transients, and overloading.** Shutting down grid is very risky. On and off is when you have the problems. It is not realistic.
- Allowing the grid to fail will damage transformers. **"Switch on/off – there have been transformer failures from trying to put the system back online. Turning back on could cause many problems...when things go down too quickly, things go wrong."**
- Best policy is to protect the grid to operate through a large GIC event. "Fight to the last breath to keep the system running."
- **Transformers will need E3/GMD protection**. E3 levels roughly an order of magnitude higher.
- **Neutral blocking device in Wisconsin [SolidGround®]...working as designed**
- GIC protection from GMD and E3 HEMP should be addressed concurrently
- Transformer protection is a low hanging fruit.
- **IEC International EMP Standard (IEC 61000-2-9) provides useful waveforms**

Myth #11 — "European data accurately represent U.S. GMD risks."

Fact. The U.S. grid is more exposed than most European systems because of **geologic conductivity,** geomagnetic **latitude**, and because our network includes **longer east-west transmission corridors**. U.S.-specific research—such as **ORNL's** *Geomagnetic Storms and Their Impacts on the U.S. Power Grid* (**Meta-R-319**, 2010)

https://www.futurescience.com/emp/ferc_Meta-R-319.pdf shows **greater impacts** than European models predict. Importing European parameters into North American planning **systematically understates** the hazard.

Myth #12 — "Space weather effects on the grid are invisible and negligible."

Fact. Space weather impacts are **measurable** in dollars and claims. **Zurich (2015)** linked GMDs to increased **electrical equipment failures**, quantifying a visible economic burden from this "invisible force" on the order of **$10 billion per year ($15 billion in 2025 dollars)**. See: *Electrical Claims and Space Weather: Measuring the Visible Effects of an Invisible Force* (Zurich, 2015), https://centerforsecuritypolicy.org/wp-content/uploads/2022/06/Appendix-F-2015Zurich-ElectricalClaimsandSpaceWeather.pdf

Myth #13 — "The grid's design—interconnectivity and long corridors—delivers efficiency without needing additional GIC protections."

Fact. The very features that boost efficiency—**interconnectivity**, **long high-voltage corridors**, and large **loop areas**—amplify GIC risk per **Faraday's Law**. Even **moderate** events can inject meaningful current into transformer neutrals. Efficiency and reliability are not the same thing; absent hardware that **blocks GIC entirely** (see *Proven and Cost-Effective Mitigation – Keeping GIC Out of Transformers*, p. 4), efficiency-driven topology can convert a space-weather fluctuation into a system-wide vulnerability.

Myth #14 — "Grid decay from HEMP E3 is gradual and manageable."

Fact. E3 HEMP produces **rapid GIC peaks** that bias cores into saturation quickly, increasing the likelihood of **transformer damage, harmonics** and **blackouts**. The notion of a slow, easily managed decay ignores both measured signatures and system dynamics. For detail, see **ORNL**, *The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid* (**Meta-R-321**, 2010): https://www.ferc.gov/sites/default/files/2020-05/ferc_meta-r-321.pdf

These myths are no longer tenable. The physics, the operational experience, and the economic evidence all point in the same direction: targeted, hardware-based **GIC blocking** is practical, proven, and vastly cheaper than the status quo. Dispelling misinformation clears the way for the only responsible course— **immediate deployment of capacitive neutral-blocking devices on the ~6,000 large power transformers identified "high risk designs" to GIC (quickest to half-cycle saturate) in order to protect those transformers, and protect the grid *from* those transformers**—so that the next severe solar storm or a potential HEMP event does not become a preventable national catastrophe.

Appendix III – "SAVE Transformers"
Secretary of Energy Emergency Order Template

Order No. _____

Pursuant to the authority vested in the Secretary of Energy by section 202(c) of the Federal Power Act (FPA) and section 301(b) of the Department of Energy (DOE) Organization Act and for the reasons set forth below, I hereby determine that an emergency exists across the continental United States due to a vulnerability of high voltage transformers to geomagnetically induced currents, also known as ground induced currents (GICs), and that issuance of this Order will meet the emergency and serve the public interest.

Findings

America's electric grid, integral to every aspect of modern life, faces existential threats from solar weather [through coronal mass ejections (CMEs) that cause geomagnetic disturbances (GMDs)] and high altitude nuclear electromagnetic pulse (HEMP), both capable of crippling electric power systems. The high voltage transformers critical to sustaining the electric grid are vulnerable to geomagnetically induced currents, also known as ground induced currents (GICs), which are induced in the earth by naturally occurring geomagnetic disturbances (GMDs) or the late-time (E3) component of high altitude electromagnetic pulse (HEMP) and enter the electric grid through the ground connected neutral wires of transformers.

The Extra High Voltage (EHV) transformers (345 kV – 765 kV) are the most vulnerable to GIC per their design (as they half-cycle saturate at very low GIC), are also the hardest to replace, many of them custom made with production lead times as long as 4-6 years, and require massive logistical and transportation challenges during their replacement process even during ideal "blue sky" conditions with a fully functioning grid, economy and society.

The GIC threat posed to these critical transformers is dependent on numerous factors, including the transformer's size, design and age, the ground conductivity in the region of the electric grid, and magnetic field produced by GMD or E3 HEMP.

In June 1992, the Electric Power Research Institute found that the aging of power transformers increases their susceptibility to GIC due to degraded insulating oil condition and coil condition (see "EPRI TR-100450, 1992").

In January 2021, The National Security Council recommended "that U.S. electrical systems and other critical infrastructure elements can be assessed for disruption and damage susceptibility up to the benchmark HEMP waveforms characterized by peak electric field strengths of 80 V/km for E3a (blast), and 50 V/km for E3b (heave), respectively," (See "Final HEMP Memo January 12, 2021 – Department of Energy").

In May 2025, the International Electrotechnical Commission (IEC) updated its international standard for E3 HEMP to a peak electric field strength environment of 85 V/km (see "IEC 61000-2-9, Edition 2.0 2025-05").

The current standard established by the North America Electric Reliability Corporation (NERC) to protect transformers and the grid from failure due to GIC, fails to require utilities to consider the design type and

age of their transformers, establishes a "benchmark" peak electric field of only 8 V/km in Quebec, and utilizes a "scaling factor" to allow utilities to "scale down" per their geomagnetic latitude to consider a peak electric field of ~2 V/km across the center of CONUS and only 0.8 V/km across the southern states (while the GMD threat often decreases with geomagnetic latitude, the E3 HEMP threat is higher at lower geomagnetic latitudes due to its generation mechanism), engendering the real possibility of wide-area GIC-caused blackout with transformer and grid equipment failures (see "NERC TPL-007").

ORDER

Given the above circumstances, I have determined that it is necessary and in the public interest for the United States of America that all covered entities conduct a survey of covered equipment to determine vulnerabilities to GIC.

> Covered entities include every electric utility and electric project developer, owner and operator, regardless of ownership or operation by the public or private sector within the state, regardless of whether that utility is subject to the jurisdiction of the North American Electric Reliability Corporation (NERC), and regardless of the regional transmission operators or independent system operators with which it operates.
>
> Covered equipment includes all power transformers with primary voltage of 100 kV or greater and capacity of 25 MVA or greater and all Generator Step-Up (GSU) transformers with secondary voltage of 100 kV or greater and capacity of 25 MVA or greater

Based on my determination of an emergency set forth above, I hereby order:

A. Every covered entity shall conduct a technical assessment survey of all covered equipment within its jurisdiction to determine its vulnerability to geomagnetically induced currents, also known as ground induced currents (GICs), which are induced in the Earth by naturally occurring geomagnetic disturbances (GMDs) or the late-time (E3) component of high-altitude electromagnetic pulse (HEMP).

B. Specifically, covered entities shall use the analytic waveform plotted in Figure A.5 of "IEC 61000-2-9, Edition 2.0 2025-05" in their operating models to determine the susceptibility of their transformers to GICs associated with a peak magnetic field strength environment of 20,000 nT for E3 HEMP, which for a typical low conductivity ground conductivity in the United States will produce a peak electric field environment of 85 V/km, based on the recently updated International Electrotechnical Commission (IEC) international standard. (Evaluating the worst-case E3 HEMP threat to high voltage transformers and the grid will also consider severe GMD threats.)

C. Covered entities shall undertake GIC modeling under the assumption that their transformers are operating fully loaded at the time when the operating environment experiences the GIC insult utilizing the late-time E3 HEMP waveform in IEC 61000-2-9, Edition 2.0 2025-05.

D. Because the aging of power transformers increases their susceptibility to GIC due to degraded insulating oil condition and coil condition, covered entities shall consider the age of the transformers surveyed and de-rate those transformers according to ANSI/IEEE Standard C57.110 and IEEE Standard C57.91 when analyzing transformer susceptibility. After confirming and considering the age, condition, and loading of each transformer, the peak geoelectric operating environment (e.g. 85 V/km), and the ground conductivity profile, covered entities shall identify which transformers would be susceptible to the following effects: (a) Half-cycle saturation (b) GIC induced harmonics; (c) VAR consumption; and, (d) Generation of hot spots in the core or

structural elements, (e) oil or insulation degradation, and report the potential impacts of each variable's susceptibility to GIC.

E. No later than 180 days from the passage of this order, and while utilizing strict operational security for Critical Energy Infrastructure Information (CEII), covered entities shall provide a detailed report to (_Insert DOE Recipient__) with copies to their state's public utility commission, to the governor and appointed chief of homeland security, and to the state legislature.

F. The report shall contain the following data for all transformers and substations found to be susceptible to GIC based on the above survey parameters: (a) Transformer Brand (b) Transformer Place of Origin [nation where manufactured] (c) Transformer Design Specifications [i.e. windings and core configuration, winding impedances, winding DC resistances (specify whether assumed or measured), 1 phase vs. 3 phase, capacity (MVA), voltage (kV) (d) Transformer Age (e) Transformer Site Location [redacted for CEII] (f) Transformer Purpose [GSU, Auto, Step-down, Converter] (g) Transformer Replacement Lead Time and Replacement Cost.

G.   In addition to providing the above data in spreadsheet form, covered entities shall consider how to most expeditiously protect their transformers from GIC, based on the totality of the circumstances (design, purpose, age, replacement lead time, etc.).

H. Covered entities shall not consider "operating procedures" such as load shedding and VAR supply as sufficient forms of GIC protection since adverse GIC effects can occur rapidly (may be no warning with E3) and over large regions that overwhelm operational reaction capabilities, and procedures cannot block GIC from entering an operating electric grid.

I. The report shall also provide the following: (a) Recommended solutions to protect the grid against GIC by preventing or reducing the half-cycle saturation of transformers, (b) Total cost to implement GIC protection of all vulnerable transformers owned and operated by the covered entity and (c) a priority list of transformers considering individual transformer risk, transformers threat to the remaining grid if unprotected (half-cycle saturating generating harmonics) and associated critical infrastructure/service loss.

J. As part of this report, covered entities shall also provide their recommendations for funding the deployment of this GIC protection, which can include both government grant opportunities and rate recovery.

K. This Order shall be effective from _____ on _____, and shall expire at 00:00 AM EST on ____. Renewal of this Order, should it be needed, must be requested before this Order expires.

Issued in Washington, D.C. at _____.

_____
Chris Wright
Secretary of Energy

cc: FERC Commissioners
    Chairman Laura V. Swett
    Commissioner David Rosner
    Commissioner Lindsay S. See
    Commissioner Judy W. Chang

Appendix IV – "SAVE Transformers" Act – Long Version

AN ACT requiring utilities and electric grid operators to assess and report the vulnerability of high-voltage transformers to geomagnetic and electromagnetic disturbances, and to recommend mitigation measures to protect the state electric infrastructure.

Findings:

1.] America's electric grid, integral to every aspect of modern life, faces existential threats from solar weather [through coronal mass ejections (CMEs) that cause geomagnetic disturbances (GMDs)] and high altitude nuclear electromagnetic pulse (HEMP), both capable of crippling electric power systems; and

2.] The high voltage transformers critical to sustaining the electric grid are vulnerable to geomagnetically induced currents, also known as ground induced currents (GICs), which are induced in the earth by naturally occurring geomagnetic disturbances (GMDs) or the late-time (E3) component of high altitude electromagnetic pulse (HEMP) and enter the electric grid through the ground connected neutral wires of transformers; and

3.] The Extra High Voltage (EHV) transformers (345 kV – 765 kV) are the most vulnerable to GIC per their design (as they half-cycle saturate at very low GIC), are also the hardest to replace, many of them custom made with production lead times as long as 4-6 years, and require massive logistical and transportation challenges during their replacement process even during ideal "blue sky" conditions with a fully functioning grid, economy and society; and

4.] The GIC threat posed to these critical transformers is dependent on numerous factors, including the transformer's size, design and age, the ground conductivity in the region of the electric grid, and magnetic field produced by GMD or E3 HEMP; and

5.] In June 1992, the Electric Power Research Institute found that the aging of power transformers increases their susceptibility to GIC due to degraded insulating oil condition and coil condition (see "EPRI TR-100450, 1992"); and

6.] In January 2021, The National Security Council recommended "that U.S. electrical systems and other critical infrastructure elements can be assessed for disruption and damage susceptibility up to the benchmark HEMP waveforms characterized by peak electric field strengths of … 80 V/km for E3a (blast), and 50 V/km for E3b (heave), respectively," (See "Final HEMP Memo January 12, 2021 – Department of Energy"); and

7.] In May 2025, the International Electrotechnical Commission (IEC) updated its international standard for E3 HEMP to a peak electric field strength environment of 85 V/km (see "IEC 61000-2-9, Edition 2.0 2025-05"); and

8.] The current standard established by the North America Electric Reliability Corporation (NERC) to protect transformers and the grid from failure due to GIC, fails to require utilities to consider the design type and age of their transformers, establishes a "benchmark" peak electric field of only 8 V/km in Quebec, and utilizes a "scaling factor" to allow utilities to "scale down" per their geomagnetic latitude to consider a peak electric field of ~2 V/km across the center of CONUS and only 0.8 V/km across the

southern states (while the GMD threat often decreases with geomagnetic latitude, the E3 HEMP threat is higher at lower geomagnetic latitudes due to its generation mechanism), engendering the real possibility of wide-area GIC-caused blackout with transformer and grid equipment failures (see "NERC TPL-007");

Therefore,

The State of __ (Insert State Name)____hereby establishes the "SAVE [Survey All Vulnerable Electric Transformers Act] Transformers Act", to be managed by _ (Insert State Agency)___.

Definitions:

1.] Covered entities: entities covered by this act include every electric utility and electric project developer, owner and operator, regardless of ownership or operation by the public or private sector within the state, regardless of whether that utility is subject to the jurisdiction of the North American Electric Reliability Corporation (NERC), and regardless of the regional transmission operators or independent system operators with which it operates.

2.] Covered equipment: includes all power transformers with primary voltage of 100 kV or greater and capacity of 25 MVA or greater and all Generator Step-Up (GSU) transformers with secondary voltage of 100 kV or greater and capacity of 25 MVA or greater.
Requirements:

Every covered entity shall by (_____(Insert Date)_____) conduct a technical assessment survey of all covered equipment within its jurisdiction to determine its vulnerability to geomagnetically induced currents, also known as ground induced currents (GICs), which are induced in the Earth by naturally occurring geomagnetic disturbances (GMDs) or the late-time (E3) component of high altitude electromagnetic pulse (HEMP); and,

1.] Specifically, covered entities shall use the analytic waveform plotted in Figure A.5 of "IEC 61000-2-9, Edition 2.0 2025-05" in their operating models to determine the susceptibility of their transformers to GICs associated with a peak magnetic field strength environment of 20,000 nT for E3 HEMP, which for a typical low conductivity ground conductivity in the United States will produce a peak electric field environment of 85 V/km, based on the recently updated International Electrotechnical Commission (IEC) international standard. (Evaluating the worst-case E3 HEMP threat to high voltage transformers and the grid will also consider severe GMD threats.)

2.] Covered entities shall undertake GIC modeling under the assumption that their transformers are operating fully loaded at the time when the operating environment experiences the GIC insult utilizing the late-time E3 HEMP waveform in IEC 61000-2-9, Edition 2.0 2025-05.

3.] Because the aging of power transformers increases their susceptibility to GIC due to degraded insulating oil condition and coil condition, covered entities shall consider the age of the transformers surveyed and de-rate those transformers according to ANSI/IEEE Standard C57.110 and IEEE Standard C57.91 when analyzing transformer susceptibility. After confirming and considering the age, condition, and loading of each transformer, the peak geoelectric operating environment (e.g. 85 V/km), and the ground conductivity profile, covered entities shall identify which transformers would be susceptible to the following effects: (a) Half-cycle saturation (b) GIC induced harmonics; (c) VAR consumption; and, (d) Generation of hot spots in the core or structural elements, (e) oil or insulation degradation, and report the potential impacts of each variable's susceptibility to GIC.

4.] No later than 180 days from the passage of this act, and while utilizing strict operational security for Critical Energy Infrastructure Information (CEII), covered entities shall provide a detailed report to (_Insert Agency__) with copies to the public utility commission, to the governor and appointed chief of homeland security, and to the state legislature.

5.] The report shall include, for each susceptible transformer and substation: Transformer brand; transformer place of origin, including nation where manufactured; transformer design specifications, including windings and core configuration, winding impedances, winding DC resistances (specify whether assumed or measured), and phase type (single-phase or 3-phase); transformer capacity in megavolt-amperes (MVA); transformer voltage level in kilovolts (kV); transformer age; transformer site location, redacted for CEII; transformer purpose (e.g., generator step-up, autotransformer, step-down, converter), redacted for CEII; transformer replacement lead time; and transformer replacement cost.

6.] In addition to providing the above data in spreadsheet form, covered entities shall consider how to most expeditiously protect their transformers from GIC, based on the totality of the circumstances (design, purpose, age, replacement lead time, etc.).

7.] Covered entities shall not consider "operating procedures" such as load shedding and VAR supply as sufficient forms of GIC protection since adverse GIC effects can occur rapidly (may be no warning with E3) and over large regions that overwhelm operational reaction capabilities, and procedures cannot block GIC from entering an operating electric grid.

8.] The report shall also provide the following: (a) Recommended solutions to protect the grid against GIC by preventing or reducing the half cycle saturation of transformers, (b) Total cost to implement GIC protection of all vulnerable transformers owned and operated by the covered entity and (c) a priority list of transformers considering individual transformer risk, transformers threat to the remaining grid if unprotected (half-cycle saturation harmonic generation) and associated critical infrastructure/service loss.

9.] As part of this report, covered entities shall also provide their recommendations for funding the deployment of this GIC protection, which can include both government grant opportunities and rate recovery.

This act takes effect at __(Insert Date)_____.

Appendix V – "SAVE Transformers" Act – Short Version

AN ACT requiring utilities and electric grid operators to assess and report the vulnerability of high-voltage transformers to geomagnetic and electromagnetic disturbances, and to recommend mitigation measures to protect the state electric infrastructure.

1. Short title. This chapter shall be known as "Survey All Vulnerable Electric [SAVE] Transformers Act."

2. Findings.

I. America's electric grid is critical to modern life and faces existential threats from solar weather events (coronal mass ejections—CME), geomagnetic disturbances—GMDs, and high altitude nuclear electromagnetic pulse—HEMP, all capable of disabling electric power systems.

II. High voltage transformers are especially vulnerable to geomagnetically induced currents—GICs—whether induced by GMDs or HEMP E3 component, entering the grid through ground-connected neutral wires.

III. Extra High Voltage (EHV) transformers (345 kV–765 kV) are most vulnerable and difficult to replace, with production lead times of up to 4–6 years.

IV. GIC vulnerability is influenced by transformer characteristics, ground conductivity, and the magnetic field intensity from GMD or E3 HEMP.

V. Aging transformers are more susceptible to GIC due to degraded insulating oil and coil condition.

VI. Federal and international standards highlight the importance of transformer assessment and protection against these threats.

SURVEY ALL VULNERABLE ELECTRIC TRANSFORMERS ACT

A:1 Purpose. The purpose of this chapter is to require electric utilities and electric project developers to assess and report the vulnerability of high-voltage transformers to geomagnetically induced currents (GICs) caused by geomagnetic disturbances (GMDs) and high altitude electromagnetic pulse (HEMP), and to recommend mitigation strategies to protect critical electric infrastructure.

A:2 Definitions. In this chapter:

I. "Covered entity" means any electric utility or electric project developer, owner, or operator within the state, regardless of public or private ownership or jurisdiction under the North American Electric Reliability Corporation (NERC).

II. "Covered equipment" means any power transformer with a primary voltage of 100 kV or greater and capacity of 25 MVA or greater, and any generator step-up transformer with a secondary voltage of 100 kV or greater and capacity of 25 MVA or greater.

III. "GIC" means geomagnetically induced current, also known as ground induced current, resulting from naturally occurring GMDs or the late-time (E3) component of HEMP.

IV. "Critical energy infrastructure information protocols," "critical electric infrastructure information protocols," or "CEII" means specific engineering, vulnerability, or detailed design protocols and procedures related to proposed or existing critical infrastructure, whether physical or virtual, that relate to the production, generation, transmission, transportation, or distribution of energy, the unauthorized disclosure of which could pose a risk to the security, reliability, or integrity of the infrastructure; such protocols are designated as confidential and exempt from public disclosure, as their release could be useful to a person planning an attack or otherwise causing harm to the infrastructure.

A:3 Assessment Requirements.

I. Each covered entity shall, no later than January 1, 2027, conduct a technical assessment of all covered equipment to determine vulnerability to GICs.

II. The assessment shall:

(a) Utilize the waveform in Figure A.5 of IEC 61000-2-9, Edition 2.0 (2025-05), modeling a peak magnetic field strength of 20,000 nT and corresponding electric field of 85 V/km.

(b) Assume transformers are fully loaded during GIC exposure.

(c) Account for transformer age and condition using ANSI/IEEE Standard C57.110 and IEEE Standard C57.91.

(d) Identify susceptibility to half-cycle saturation, GIC-induced harmonics, reactive power consumption, hot spot generation, and insulation degradation.

A:4 Reporting Requirements.

I. No later than 180 days after passage of this act, each covered entity shall submit a report to the U.S. Department of Energy, with copies to the public utilities commission, the governor, the chief of homeland security, and the legislature.

II. The report shall include, for each susceptible transformer and substation:

a) Transformer brand; transformer place of origin, including nation where manufactured; transformer design specifications, including windings and core configuration, winding impedances, winding DC resistances (specify whether assumed or measured), and phase type (single-phase or 3-phase); transformer capacity in megavolt-amperes (MVA); transformer voltage level in kilovolts (kV); transformer age; transformer site location, redacted for CEII; transformer purpose (e.g., generator step-up, autotransformer, step-down, converter), redacted for CEII; transformer replacement lead time; and transformer replacement cost.
(b) Spreadsheet-formatted data and narrative analysis.
(c) Recommended solutions to protect the grid against GIC by preventing or reducing the half cycle saturation of transformers.
(d) Total cost to implement GIC protection.
(e) Priority list of transformers by damage risk and critical infrastructure impact.
(f) Funding recommendations, including potential grant sources and rate recovery mechanisms.

A:5 Operational Standards. Covered entities shall not rely solely on operational procedures such as load shedding or reactive power supply to mitigate GIC risk. Such procedures shall not be considered sufficient protection under this chapter.

A:6 Confidentiality. All data submitted under this chapter shall be handled in accordance with CEII protocols as defined in A:2. Location and purpose data shall be redacted from public reports.

Effective Date. This act shall take effect _____.

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Next Steps - Stay Informed and Engaged

This report addresses urgent national security matters that require immediate and decisive action. The urgency is heightened by a range of historical and persistent challenges, including bureaucratic inertia, regulatory capture, political influence, and the pursuit of profit. Given the complexity and evolving nature of these issues, it is both wise and necessary to enable this report to be actively updated.

To support this adaptability, a QR code has been included with this report. By scanning the code, readers will gain access to a webpage hosting the latest version of this report as well as additional educational material, media articles, and real-time updates regarding legislative resolutions, bills, and executive actions at both the federal and state levels.

Public monitoring of federal and state executive, legislative, and regulatory actions is essential for maintaining oversight and accountability. Our Coalition thus urges "We the People" to stay engaged.

CENTER
FOR SECURITY POLICY

Exhibit L

Comments of Secure the Grid Coalition on DOE "Speed to Power" RFI (2025-18058).
Secure the Grid Coalition. November 21, 2025.

Secure the Grid Coalition
A Project of the Center for Security Policy
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November 21, 2025

U.S. Department of Energy
1000 Independence Ave, SW
Washington, DC 20585

Comments of Secure the Grid Coalition on DOE "Speed to Power" RFI (2025-18058)

Dear Department of Energy:

Our Secure the Grid Coalition[1] urges the Department of Energy to act aggressively to protect our nation's electric grid against threats which produce Geomagnetically Induced Currents (GIC). GIC results from regularly occurring solar storms. GIC can also result from the detonation of a nuclear warhead in the upper atmosphere, a so-called High-Altitude Electromagnetic Pulse (HEMP) attack. Fortunately, commercially available, thoroughly validated, and cost-effective technology already exists to protect against both threats—the capacitive neutral blocking device known as SolidGround®.

Whatever you build will stand or fall depending on the firmness of its foundation.

As our comments below will demonstrate, DOE's exciting "Speed to Power" initiative and the future of American energy are at risk of failure <u>due to the lack of a firm foundation</u> protecting our electric grid from **GIC threats that could eventually destroy it.**

Absent protections, the next extreme solar storm could collapse the U.S. electric grid, resulting in millions of deaths—and potential loss of continuity of government. Comprehensive protection against solar storms would also mitigate the long pulse [also known as the "E3 Pulse"] from a HEMP attack.

Thus, nationwide GIC protection will rapidly bolster America's nuclear deterrence against peer adversaries and rogue nations seeking to exploit the asymmetric warfare benefits of a HEMP attack.

Deploying SolidGround® to protect America's roughly 6,000 identified "high risk design" transformers is a one-time cost of ~ $4 billion. This hardware protection will also save the U.S. ~ $10 billion in annual economic losses from GIC effects due to routine solar weather. <u>This is a commonsense investment</u>.

Our present warning and recommendations are a re-add; of those we voiced previously to DOE in August 2020[2], and to the previous Secretary of Energy in January 2022[3], June 2022[4] and April 2024[5].

While the <u>previous leadership chose not to act</u>, we have firm faith that the present leadership will.

We just hope you will act in time.

[1] The Secure the Grid Coalition is a group of policy, energy, and national security experts dedicated to strengthening the resilience of America's electrical grid. It is sponsored by the Center for Security Policy, a 501(c)(3) nonprofit which receives no funding from governments, foreign sources, the electric industry, or any for-profit corporations involved in protecting the grid, including EMPRIMUS, which has developed the capacitive neutral blocking device known as SolidGround®

[2] https://securethegrid.com/wp-content/uploads/2021/02/STG-Coalition-Comments-on-DOE-RFI-24-Aug-2020.pdf

[3] https://securethegrid.com/wp-content/uploads/2025/11/STG-Coalition-Letter_to_DOE_on_Supply_Chain_RFI_Jan_2022.pdf

[4] https://centerforsecuritypolicy.org/wp-content/uploads/2022/06/STG-Coalition-Comments-SEAB-13June2022-Final.pdf

[5] https://securethegrid.com/wp-content/uploads/2025/11/STG-Coalition-Comments-SEAB-9April2024-with_Photos_and_Enclosure.pdf

National Context and Alignment with Executive Order 14262

The Department of Energy's (DOE) Request for Information (2025-18058) cites President Trump's Executive Order 14262 (Strengthening the Reliability and Security of the United States Electric Grid, April 8, 2025) as one of the guiding authorities for accelerating large-scale generation and transmission expansion. That Executive Order recognizes that America's ability to maintain economic, technological, and military superiority depends upon an electric grid that is **both reliable and secure** in the face of surging demand from artificial-intelligence data centers, advanced manufacturing, and semiconductor fabrication facilities.

EO 14262 establishes a clear national policy:

"It is the policy of the United States to ensure the reliability, resilience, and security of the electric power grid… our electric grid must utilize all available power generation resources, particularly those secure, redundant fuel supplies that are capable of extended operations."

In direct support of that policy, DOE is instructed to:

- streamline/systemize use of its emergency authority under § 202(c) of the Federal Power Act,

- create a uniform reserve-margin methodology for all regions, and

- identify and protect generation resources "critical to system reliability."

These provisions make EO 14262 the natural home for actions that address the threat of GICs that are the main impact of both Geomagnetic Disturbances (GMD) and E3 HEMP —phenomena that, if ignored, could abruptly erase the reserve margin and reliability the Executive Order directs DOE to safeguard.

Ultimately, the "Speed to Power" initiative cannot succeed if invisible currents in the earth induced by space weather or from hostile actors are allowed to destroy the very transformers, large power generators and high voltage circuit breakers that make "speed to power" possible.

Existing Reliability Gaps That Undermine the Executive Order's Purpose

A. Regulatory Capture and Reliability Standards Based on Analytical Error

Current electric grid protections against GIC are woefully inadequate, because the threat thresholds in reliability standards developed by the North American Electric Reliability Corporation (NERC) are a small fraction of what has already occurred in the real world. Our detailed technical explanation follows.

The electric field strength of both GMD and E3 HEMP is measured in volts per kilometer (V/km) and directly relates to how large the GIC currents will be.

Our Secure the Grid Coalition's recent report **"*Speed to Power on a Firm Foundation*"** documents in detail how current NERC standards fail to meet EO 14262's requirement for genuine reliability as it relates to the GIC threat.[6]

The Nuclear Regulatory Commission's (NRC) May 7, 2025 decision denying Petition for Rulemaking PRM-50-96 —despite warnings from the Air Force Electromagnetic Defense Task Force, the GAO, EMP Commission, International Electrotechnical Commission (IEC) and the National Academies— epitomizes this institutional blunder. NRC justified its action based on the FERC-approved NERC

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[6] The report, "Speed to Power on a Firm Foundation" can be found here: https://securethegrid.com/save/

geomagnetic-disturbance standard (TPL-007-4) and the untrue assertion that "80 percent of EHV transformers are resistant to GICs."

But NERC TPL-007-4 is analytically indefensible. It was specifically designed to ensure that the utility industry could "comply" without actually taking any actions whatsoever to prevent GIC-induced harm to the electric grid. The standard was derived not from U.S. data, but from European magnetometer data collected during 21 years of unusually low solar activity and then spatially averaged to reduce field intensities. The result was a "benchmark storm" of only 8 volts per kilometer (V/km) at 60° geomagnetic latitude over Quebec, scaled down to 4 V/km in the northern U.S., 2 V/km in the central U.S., and 0.8 V/km in the south. These levels of "required protection" in fact require no protection at all from GIC.

Meanwhile, recent empirical research by the U.S. Geological Survey (USGS) shows that this benchmark underestimates reality by more than an order of magnitude. The 1989 Hydro-Québec storm produced field strengths of 19–22 V/km in Virginia, Maine, and Connecticut—**over seven times the NERC benchmark** for those areas.

Such miscalibration leaves the bulk power system unprepared for even moderate recurrence events, let alone a Carrington-class superstorm or an E3 HEMP attack. It is important to note that while the GMD threat often decreases with geomagnetic latitude, the **E3 HEMP works in the reverse with a higher electric field strength at lower geomagnetic latitudes,** due to its generating mechanism.

This means the **southern states will get hit with the most severe GIC from an E3 HEMP attack** with field strengths as high as 85 V/km at 40° geomagnetic latitude (International Standard IEC 61000-2-9) and will be the least prepared anticipating only 0.8 V/km per the NERC standard.

The graphic below shows the NERC Standard versus the real-world GIC threats associated with both solar weather and nuclear E3 HEMP.

NERC Standard vs. GIC Threat
GIC Magnitude Comparison

The electric field strength of GMD and E3 HEMP events are measured in volts per kilometer (V/km) which directly relates to how large the ground induced currents (GIC) will be.

- ■ NERC Benchmark set @ 60° geomagnetic latitude (Quebec, Canada)
- ■ NERC Standard for **Washington D.C.** ~ 2 V/km @ 49° across center of U.S.
- ■ NERC Standard for **Texas, Florida**... 0.8 V/km @ 40° across southern states
- ■ NY Railroad Solar Storm 1921 (**20 V/km**)
- ■ Carrington Event 1859 (**> 20 V/km**)
- ■ Soviet E3 HEMP Tests 1962 (*achieved* **66 V/km** @ 49°)
- ■ Congressional EMP Commission E3 HEMP (**85 V/km** for Continental U.S.)
- ■ IEC E3 HEMP Standard: updated May 2025 (**85 V/km** *and above*)

Moreover, geomagnetic storm intensity as reported by NOAA and others that study the solar phenomena is measured in nanoteslas (nT) for purposes of comparing events. This does not correctly compare, nor is it the function of solar scientists to compare, the extent of damage that a solar event could inflict on the power grid. The correct measurement to compare the intensities of ground induced currents (GIC) from a solar event is nanotesla per minute (**nT/min**). It is the **rate-of-change** that is the determining factor in the magnitude of ground-induced currents. According to Faraday's Law of Induction, a faster rate-of-change in magnetic flux results in a greater induced voltage. The nT comparison of solar storms is inaccurate and misleading when considering the space weather threat to our power grid. Example: it is the nT comparison that leads some to the belief that the 1989 Quebec Storm was 50% the estimated size of the 1859 Carrington Event when in actuality it was less than 10% the size as it relates to GIC magnitude due to the rate-of-change (nT/min.)

B. The Aging Transformer Fleet Exacerbates Vulnerabilities

Section 2 of EO 14262 calls for "secure, redundant fuel supplies that are capable of extended operations." Yet the very transformers that deliver that fuel are old and fragile. DOE's *own Large Power Transformer and the U.S. Electric Grid* study reported an average transformer age of 38–40 years, with 70 percent over 25 years old. These units were never designed for quasi-DC currents. Their cellulose insulation and dielectric oils degrade with age, magnifying susceptibility to half-cycle saturation, harmonic generation, overheating, and catastrophic failure during GIC events. This informs further the NRC's declaration that "80 percent of EHV transformers are resistant to GICs" is without foundation.

C. Slow Standard Setting Is Not a Solution

The FERC/NERC process averages nearly a decade per standard. Order 779 (2013) directing GMD protections led to TPL-007-1 (2016), then -2 (2018), -3 (2019), and -4 (2020), none of which corrected the fundamental error in the benchmark storm. By contrast, EO 14262 empowers DOE to act now under existing law – an authority that should be exercised before the next solar maximum peaks in 2026–27.

Deploying the Validated Solution: Capacitive Neutral Blocking Technology

A. GIC Mitigation Hardware

A commercially available and cost-effective solution already exists - capacitive neutral blocking devices. The SolidGround® capacitive Neutral Blocking Device (NBD), developed by EMPRIMUS and validated by the Department of War's Defense Threat Reduction Agency (DTRA), Idaho National Laboratory (INL), Oak Ridge National Laboratory (ORNL) and the Department of Energy (DOE) under Contract [No. 89503421PWA001210] automatically blocks GIC (quasi-DC currents) from entering transformers without affecting AC grounding or fault-current handling.

SolidGround® is a closed system (no tampering with existing AC controls) that simply attaches to the transformer's neutral ground cable and automatically blocks GIC at the point of entry whenever detected. The device has been operating for over a decade on our bulk power grid at the 345 kV and 500 kV level in the American Transmission Company (ATC), Western Area Power Administration (WAPA) and Tennessee Valley Authority (TVA) fleets performing as designed without failure. These three utilities have all contributed to the design of SolidGround® and have co-written papers, published articles, written reports and submitted testimony to the U.S. Senate Committee on its performance.

SolidGround® is now being purchased and installed internationally, but there is no regulatory requirement for its mitigative technology in the United States. Foreign nations are purchasing SolidGround® legitimately while it appears that the People's Republic of China has been stealing the intellectual property and is apparently installing a version of it in the Chinese grid.

B. Cost and Scalability

Each SolidGround® unit costs approximately USD $500,000 and is standardized – able to be produced on an assembly line. Nationwide deployment on the estimated 6,000 critical large power transformers identified as "high risk designs" to GIC (the first to half-cycle saturate) would cost ≈ $3–4 billion (including installation)—less than 0.5 percent of the 2021 Infrastructure Investment and Jobs Act [7].

By contrast, routine space-weather losses from low-level GIC entering the power grid already costs the U.S. economy approximately $10 billion annually (Zurich, Lockheed Martin and NOAA study 2015). A single Carrington-class space weather event occurring today is estimated to inflict $0.6–2.6 trillion in losses based solely on the value of lost load (Lloyd's of London 2013)[8].

The benefit-cost ratio exceeds 500:1 in purely economic terms—before considering damaged equipment, national-security losses and human costs – which could be in the tens or hundreds of millions of lives lost. While the solution has been extensively tested and independently validated by both industry and the federal government with the cost and locations defined, it has not been implemented because there is no standard or requirement to install them and utilities will not pay for the cost to protect our grid from GIC if it is not required.

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[7] https://centerforsecuritypolicy.org/for-the-cost-of-less-than-1-of-the-biden-infrastructure-bill-we-could-protect-our-electric-grid-from-certain-collapse/

[8] https://centerforsecuritypolicy.org/wp-content/uploads/2022/06/Appendix-E-Space-Weather-2014-Schrijver-Assessing-the-impact-of-space-weather-based-on-insurance.pdf

Metric	Without Mitigation	With Nationwide SolidGround® Deployment
Annual losses from routine GICs (Zurich 2015 → $10 Billion)	Continued $10 B economic loss each year in the U.S. due to GIC harmonics	Reduced/Eliminated
Transformer replacement lead time	3–6 years (Hitachi Energy estimate)	No loss of critical units
Carrington-class storm impact (Lloyd's 2013)	$0.6–2.6 trillion economic loss + potential mass casualties	Contained to minor regional outages
Implementation cost	–	$3 - 4 B (one-time)
Benefit-cost ratio	–	> 500:1

By any metric—economic, environmental, or humanitarian—the cost of inaction dwarfs the cost of implementation. A single year of routine economic losses due to low-level GIC entering our grid exceeds the entire cost of GIC mitigation deployment. Moreover, SolidGround® capacitive neutral-blocking devices enhance the resilience of fuel supply chains, data centers, and defense installations - precisely the critical loads the Executive Order was issued to protect.

Ultimately, effective GIC protection of our nation's grid will only occur once our federal government requires utilities to take action through enforceable requirements and financial incentives.

[See Appendix I – Technical basis: GIC Threat and Transformer Physics]

C. Regulatory Precedent and Funding Mechanisms

FERC's "just and reasonable" standard permits cost recovery for investments that enhance reliability. Therefore, DOE can facilitate rapid deployment of GIC protection through four existing programs:

• **Transmission Facilitation Program (TFP):** DOE should designate SolidGround® capacitive neutral-blocking installations as eligible upgrades to de-risk large transmission projects.

• **Grid Resilience and Innovation Partnerships (GRIP):** DOE should provide competitive grants for transformer hardening with SolidGround® capacitive neutral blocking devices which also provide GIC monitoring.

• **Loan Programs Office (LPO):** DOE should offer low-interest financing to utilities and manufacturers for the mass production and installation of SolidGround® capacitive neutral-blocking devices needed to rapidly deploy roughly 6,000 of these devices nationwide.

• **Defense Production Act Title III:** DOE should support domestic manufacturing of SolidGround® capacitive neutral-blocking devices as a critical-infrastructure component essential to national security.

Implementation Course of Action for the Department of Energy

1. Issue an Emergency Order to Identify GIC-Vulnerable Transformers: DOE should use the authorities granted it under Section 202(c) of the Federal Power Act (16 U.S.C. § 824a(c)), the energy emergency declared in EO 14156 (January 20, 2025), and the direction to use 202(c) authorities provided in EO 14262 (April 8, 2025) to require all ISOs/RTOs to conduct a thorough survey of all large power transformers vulnerable to GIC half-cycle saturation.

The survey would identify those that must be protected against GICs from both GMD and E3 HEMP by using credible GIC scenarios for a 100-year solar storm and E3 waveforms associated with the recently updated international IEC standard (IEC 61000-2-9, Edition 2.0 2025-05), using the standard waveform in Figure A.5, modeling a peak magnetic field strength of 20,000 nT and corresponding electric field of 85 V/km. The emergency order should direct the results of the survey to be submitted within 180 days. The order should then be extended in 6-month increments until the nation produces and deploys the sufficient number of SolidGround® capacitive neutral-blocking devices to protect the electric grid from GIC.

[See Appendix III – Proposed Secretary of Energy Emergency Order on GIC Protection]

2. Deploy SolidGround® Capacitive Neutral-Blocking Devices: DOE should start with federally owned portions of the U.S. electric grid such as the Tennessee Valley Authority (TVA), Bonneville Power Administration (BPA), Western Area Power Administration (WAPA), Southeastern Power Administration (SEPA), Southwestern Power Administration (SWPA), Alaska Power Administration (APA).

Integrating GIC Mitigation into DOE's Reserve-Margin Methodology

Section 3(b) of EO 14262 directs DOE to develop a "uniform methodology for analyzing current and anticipated reserve margins." That methodology must consider not only fuel availability and generation dispatch but also **the risk of generation loss from geomagnetic disturbances and HEMP E3 events**.

Current planning models assume that generation capacity is lost only through mechanical or fuel outages. In reality, a **single severe GMD could simultaneously disable hundreds of transformers, erasing gigawatts of reserve margin nationwide within minutes.**

Therefore, DOE should:

1. **Mandate GIC-inclusive Reserve-Margin Assessment** for all regions regulated by FERC, using credible GIC scenarios for a 100-year solar storm and E3 HEMP waveforms associated with the recently updated international IEC standard (IEC 61000-2-9, Edition 2.0 2025-05)

2. **Identify At-Risk Regions** where modeled reserve margins fall below acceptable thresholds under the same credible GIC scenarios.

3. **Direct Priority Deployment** of SolidGround® capacitive neutral-blocking devices in those regions using TFP/GRIP funding.

4. **Publish a National GIC Hazard Map** analogous to FEMA's flood-risk maps to guide state and utility investment.

Incorporating GIC risk into DOE's reserve-margin model fulfills the Executive Order's mandate to use "all available generation resources" and ensures that the Nation's emergency energy analysis is grounded in physics rather than optimism.

Conclusion

Protection against GIC threats should be an urgent priority. The Administration's recognition of a National Energy Emergency and the President's issuance of EO 14156 and EO 14262 provide DOE with both the authority and the obligation to act.

The evidence presented herein and thoroughly in our November 2025 report **"*Speed to Power on a Firm Foundation*"** demonstrate that existing FERC and NRC policies fall short of the Executive Order's requirements.

If DOE takes the steps recommended herein, the agency will fulfill the clear intent of the above Executive Orders and ensure that America's electric grid remains reliable, resilient, and secure in the face of new industrial demands and old vulnerabilities alike.

Our Secure the Grid Coalition is available and willing to assist DOE as needed in pursuit of our shared goals to Secure the Grid.

Respectfully Submitted,
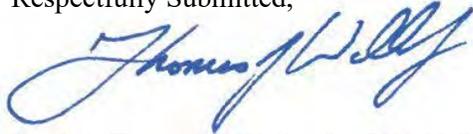
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Appendix I – Technical Basis: The GIC Threat and Transformer Physics

A. Mechanism of Damage

Geomagnetic Disturbances (GMDs) and E3 HEMP events induce low frequency, quasi-DC currents in the Earth's crust (commonly referred to as ground induced currents or "GIC") that travels the path of least resistance, <u>entering the power grid from the ground</u> through transformer ground connected neutrals. Because transformer cores are designed for pure AC operation, any DC bias (as low as a few amps GIC per phase) drives the core into half-cycle saturation. This produces three cascading effects:

1. **Harmonic generation** that can damage generator rotors, disrupt protective relays, destroy power supplies and customer equipment;

2. **Localized "hot spot" heating** that damages insulation and causes fires; and

3. **Reactive-power losses** that depress voltage across entire regions.

GIC turns large power transformers across the power grid into "harmonic generators" that destroy components all the way to the load, eventually destroying themselves and taking down the grid.

"The half-cycle saturation of the great number of large power transformers on a power system is the source of nearly all operating and equipment problems caused by GIC's during magnetic storms..."
- EPRI TR-100450, 1992

The more severe the GIC the greater the number of transformers half-cycle saturating – simultaneously injecting harmonics into the grid, and the more severe the harmonics levels generated by each transformer. It was the **GIC induced harmonics** during the 1989 Hydro-Quebec event that **collapsed Quebec's grid in 92 seconds during a modest GIC event**.

Following the Quebec event, EPRI working with Minnesota Power, injected DC into the neutrals of large power transformers of various designs at the 345kV and 500kV level to study the levels of GIC required to half-cycle saturate transformers and <u>generate harmonics</u>. **All transformer designs tested saturated at the lowest level of injected DC - 8 Amps/phase** (EPRI TR-100450, 1992).

In 2012, the Department of War's Defense Threat Reduction Agency (DTRA) was interested in the <u>GIC harmonic impact</u> to our power grid and built a substation attached to the live grid at DOE's Idaho National Laboratory to test harmonic levels generated by injecting DC into the neutral of a transformer. As GIC increased, harmonic distortion also increased. Harmonics generated at the high voltage level grow and are further enhanced as they travel towards the load (EPRI 3002002985, 2014).

It is the large power transformers **half-cycle saturating with very low GIC** that are the culprits behind the injected harmonics responsible for the estimated $10 billion in economic loss each year in the U.S. due to common low-level GIC events (Zurich, 2015). There are an estimated **6,000 large power transformers** on the U.S. grid considered "high risk design" that **half-cycle saturate with GICs as low as 2-5 Amps/phase**. This is based on GIC data and is verified by transformer engineers at ABB who have the largest collection of transformer designs that make up the U.S. fleet and have analyzed over 4,000 large power transformers on the U.S. grid as part of the NERC standard.

Golden Rule in GIC mitigation: <u>keep GIC below 6 Amps in the neutral</u> (2 Amps/phase). This prevents the largest "high risk design" power transformers from half-cycle saturating and injecting GIC induced harmonics into the power grid. International utilities have gone to extreme lengths stacking large resistors in series with additional resistors in an attempt to reduce GIC (or stray DC in the ground from HVDC operation) to below 6 Amps to prevent transformer harmonic generation. It is for this

reason SolidGround® capacitive neutral blockers for over a decade have been set to begin blocking when GIC reaches 5 Amps in the neutral...just below the 6 Amp threshold. International utilities are now beginning to tear out their large resistors and install SolidGround® which simply blocks GIC bringing it down to zero.

Blocking GIC from entering "high risk design" transformers not only protects those transformers but protects the rest of the power grid and critical components *from* those transformers.

B. The VAR Collapse Mechanism

Operators often counteract voltage depression by spinning up generation and engaging Static VAR Compensators (SVCs) and capacitor banks. This practice is counterproductive and risky during severe GIC events. When saturated transformers consume VARs and harmonics trip SVCs, system voltage plummets and blackout propagation accelerates. The correct solution is not complex operational procedures to chase and react to cascading GIC symptoms (VAR support) but to treat the cause with hardware prevention, namely, blocking GIC from entering the grid. **VAR support in a severe GIC event is dangerous and will only serve to force critical grid components to endure higher levels of GIC and harmonics over longer durations enhancing risk of catastrophic failure of those critical components.** Instead, we must block GIC and allow the power grid to operate as designed through severe GIC events without risk of damage and cascading events related to GIC.

C. Grid Failure from severe GMD and E3 HEMP

The sun has and will produce geomagnetic disturbances much larger than the hypothetical and arbitrarily low NERC TPL-007 standard. If the much larger and historical events such as the "2012 CME near miss[9]" which blasted off the back side of the sun, "1921 Railroad Event", "1859 Carrington event" and even larger "Miyake events" were to happen today, or there is a single nuclear E3 HEMP attack, **our power grid will go down very quickly due to severe levels of GIC induced harmonics - generated by transformers that are half-cycle saturating.**

On July 21, 2016, DOE held an "Electromagnetic Pulse Resilience Action Plan Meeting" with various government agencies, leading utilities in the industry, and major suppliers (DOD, INL, LANL, ABB, Siemens, Dominion, EMP Commission, EPRI, MITRE, STRATCOM, NATF, and others) to discuss our nation's EMP Resilience Action Plan and to identify specific actions "where DOE can help the most" to protect the power grid from EMP. Listed below are a few important takeaways from that meeting:

> • **Priority #1 – prevent grid failure**. GIC induced <u>Harmonics</u> from E3 HEMP and severe GMD will cause wide scale grid collapse in just 10's of seconds.
> • **Large scale load shedding is not possible**. Equipment is damaged in the shed/reconnect process due to switching transients, and overloading. Shutting down grid is very risky. On and off is when you have problems. It is not realistic.
> • **Allowing the grid to fail will damage transformers.** "Switch on/off – there have been transformer failures from trying to put the system back online. Turning back on could cause many problems...when things go down too quickly, things go wrong."
> • **Best policy is to protect the grid to operate through a large GIC event**. "Fight to the last breath to keep the system running."
> • **Transformers will need E3/GMD protection**. E3 roughly an order of magnitude higher.
> • **Neutral blocking device in Wisconsin [SolidGround®] ...working as designed**
> • **GIC protection from GMD and E3 HEMP should be addressed concurrently**
> • **Transformer protection is a low hanging fruit.**
> • **IEC EMP Standard (IEC 61000-2-9) provides useful waveforms**

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[9] https://science.nasa.gov/science-research/planetary-science/23jul_superstorm/

D. Assumptions vs. Data - "Whack-a-mole"

Whack-a-Mole is an assumption that if you block GIC in one location, it will cause GIC to be "re-directed" and spike everywhere else. Example: If you block 10 Amps GIC at one transformer, then 10 Amps GIC (or more) will be shifted somewhere else. In essence - we can't solve the GIC problem.

Fact. Over 10 years of GIC data <u>refutes</u> this assumption. To study this, **DOE under Executive Order 13744 purchased SolidGround® NBDs and installed them on the most GIC monitored grid in the U.S.** This allowed DOE to monitor GIC levels across the grid in real time as SolidGround® operated during many GMD events (of various angles), and to record that data to see the impact of blocking GIC.

DOE Objectives:

- Assess the effectiveness of SolidGround® NBDs to block GIC
- Measure any GICs re-directed to other transformers
- Use data to validate modeling and correct inaccurate assumptions

90+ SolidGround® operations analyzed by DOE, EPRI and EMPRIMUS during many GIC events

Results are consistent:

- SolidGround® NBDs operating as designed, no negative effects to power system
- GIC in neutral of protected transformer drops to zero
- Re-directed GIC is minimal and local (**V = IR**)
- **Network GIC** (sum of <u>all</u> GIC monitored on the system) **<u>decreases</u>**

NBD Impact on Protected 500kV Transformer
NBD impact can only be measured <u>the instant</u> the NBD changes the GIC circuit

Transformer Protected With SolidGround® NBD - Neutral GIC
SUNBURST and Utility 1-second Data

2024-10-08, 05:00:13 UTC

— Transformer Neutral GIC Absolute Value

Solar storm builds strength
- **GIC** in the neutral of transformer increases

SolidGround® NBD
- detects GIC (5 Amps for 5 sec.)
- GIC threshold triggers blocking
- ✓ **GIC drops to zero** in the neutral of protected transformer

Neutral GIC (Amps)

Time - Seconds From NBD Operation

Data from DOE Projects under EO 13744

NBD Impact to Neighboring Substations
NBD impact can only be measured <u>the instant</u> the NBD changes the GIC circuit

SolidGround® Neutral Blocking Device
Impact to Neighboring Sites at Operation
SUNBURST and Utility 1-second GIC Data

2024-10-08, 05:00:13 UTC

SolidGround Site
Transformer 2
Transformer 3
Transformer 4
Transformer 5
Transformer 6
Transformer 7
Transformer 8
Transformer 9
Transformer 10
Transformer 11
Transformer 12
Transformer 13
Transformer 14
Transformer 15
Transformer 16
Transformer 17

SolidGround® begins blocking:
- GIC in protected transformer drops to zero (**red line**)

✓ **Little to no impact** to neighboring substations

Storm progression

Storm progression

Neutral GIC (Amps)

Time - Seconds From NBD Operation

Data from DOE Projects under EO 13744

NBD Impact to Network GIC
NBD impact can only be measured _the instant_ the NBD changes the GIC circuit

Total Network GIC Across All Monitored Sites At SolidGround® NBD Operation
SUNBURST and Utility 1-second GIC Data

Data from DOE Projects under EO 13744

DOE's data consistently shows that **blocking GIC** in the neutral of transformers **decreases Network GIC**. (i.e. GIC is _not_ being re-directed everywhere else, **grid resilience is improving**). The more NBDs installed on the power grid, the more resilient the power grid becomes allowing the grid to operate through severe GIC events. **Modeling assumptions need to be updated to reflect the data.**

% of Transformers with SolidGround® NBDs	% Reduction of Total Network GIC	% Decrease in Reactive (VAR) Consumption
7%	13.7%	14.6%
14%	27.3%	29.3%
21%	41.0%	43.7%

Results derived from PowerWorld ™ modeling of the Wisconsin ATC Power Grid

E. "Re-directed" GIC is a concern today if we do _not_ protect the power grid

GIC will always travel the path of least resistance. During a severe GMD or E3 HEMP event, **the instant high voltage circuit breakers are operated** (intentionally via utility operating procedures or unintentionally due to GIC induced harmonics or E1 HEMP) **the GIC circuit is changed and GIC will be re-directed across the grid** in an unplanned and chaotic manner.

It is important to note that **high voltage circuit breakers** attempting to open (intentionally or unintentionally) during a severe GIC event can be catastrophically destroyed as they require "zero crossings" and **are _not_ designed to break GIC**.

Appendix II – Interagency Coordination and Federal Leadership

• **FERC:** DOE should encourage FERC to revise the TPL-007 benchmark to protect against GICs from both GMD and E3 HEMP by using credible GIC scenarios for a 100-year solar storm and E3 waveforms associated with the recently updated international IEC standard (IEC 61000-2-9, Edition 2.0 2025-05.) While the FERC/NERC process is extremely cumbersome, time consuming, and adversely affected by the utility industry through regulatory capture, the NERC standard does affect how utilities worldwide address the GIC threat. The NERC standard has vastly diminished the preparedness of modern civilizations globally to deal with the GIC threat, so it should be updated no matter how long it takes. If DOE helps set the proper incentives for the electric utility industry to be financially rewarded for properly addressing the GIC threat, the FERC/NERC rulemaking process might occur more rapidly and with better results for the public interest.

• **NRC:** DOE should encourage NRC to ensure that backup power for spent fuel pools and reactor cooling accounts for a long-term grid loss scenarios caused by GICs so that NRC can assist identifying where SolidGround® capacitive neutral-blocking devices should be installed at substations providing power to these nuclear sites.

• **DoW:** DOE should request that Department of War leadership update its (1) Mission Assurance planners [under the "resilience and energy security measures on military installations" as per 10 U.S. Code Section 2920] and its (2) Golden Dome planners to account for a long-term grid loss scenarios caused by GICs so that the Department can assist identifying where the DTRA-validated SolidGround® capacitive neutral-blocking devices should be installed at substations providing power to military bases and defense-critical centers.

• **DOE's Office of Cybersecurity, Energy Security, and Emergency Response (CESER):** CESAR should integrate SolidGround® capacitive neutral-blocking devices into the Energy Sector Lifeline Framework.

• **State Governments**: EO 14262 encourages collaboration "with such executive department and agency heads as the Secretary of Energy deems appropriate." That invitation extends to state energy offices and public utility commissions that can mandate utility resilience plans and allow cost recovery for investments in SolidGround® capacitive neutral-blocking devices. **The National Conference of State Legislatures' August 2025 resolution** urging EMP/GMD hardening provides a ready-made template for state action[10].

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[10] https://nationalinterest.org/blog/energy-world/national-conference-of-state-legislators-urges-grid-protection-from-solar-weather-emps

Appendix III – Proposed Secretary of Energy Emergency Order on GIC Protection

Order No. _____

Pursuant to the authority vested in the Secretary of Energy by section 202(c) of the Federal Power Act (FPA) and section 301(b) of the Department of Energy (DOE) Organization Act and for the reasons set forth below, I hereby determine that an emergency exists across the continental United States due to a vulnerability of high voltage transformers to geomagnetically induced currents, also known as ground induced currents (GICs), and that issuance of this Order will meet the emergency and serve the public interest.

Findings

America's electric grid, integral to every aspect of modern life, faces existential threats from solar weather [through coronal mass ejections (CMEs) that cause geomagnetic disturbances (GMDs)] and high altitude nuclear electromagnetic pulse (HEMP), both capable of crippling electric power systems. The high voltage transformers critical to sustaining the electric grid are vulnerable to geomagnetically induced currents, also known as ground induced currents (GICs), which are induced in the earth by naturally occurring geomagnetic disturbances (GMDs) or the late-time (E3) component of high altitude electromagnetic pulse (HEMP) and enter the electric grid through the ground connected neutral wires of transformers.

The Extra High Voltage (EHV) transformers (345 kV – 765 kV) are the most vulnerable to GIC per their design (as they half-cycle saturate at very low GIC), are also the hardest to replace, many of them custom made with production lead times as long as 4-6 years, and require massive logistical and transportation challenges during their replacement process even during ideal "blue sky" conditions with a fully functioning grid, economy and society.

The GIC threat posed to these critical transformers is dependent on numerous factors, including the transformer's size, design and age, the ground conductivity in the region of the electric grid, and magnetic field produced by GMD or E3 HEMP.

In June 1992, the Electric Power Research Institute found that the aging of power transformers increases their susceptibility to GIC due to degraded insulating oil condition and coil condition (see "EPRI TR-100450, 1992").

In January 2021, The National Security Council recommended "that U.S. electrical systems and other critical infrastructure elements can be assessed for disruption and damage susceptibility up to the benchmark HEMP waveforms characterized by peak electric field strengths of 80 V/km for E3a (blast), and 50 V/km for E3b (heave), respectively," (See "Final HEMP Memo January 12, 2021 – Department of Energy").

In May 2025, the International Electrotechnical Commission (IEC) updated its international standard for E3 HEMP to a peak electric field strength environment of 85 V/km (see "IEC 61000-2-9, Edition 2.0 2025-05").

The current standard established by the North America Electric Reliability Corporation (NERC) to protect transformers and the grid from failure due to GIC, fails to require utilities to consider the design type and age of their transformers, establishes a "benchmark" peak electric field of only 8 V/km in

Quebec, and utilizes a "scaling factor" to allow utilities to "scale down" per their geomagnetic latitude to consider a peak electric field of ~2 V/km across the center of CONUS and only 0.8 V/km across the southern states (while the GMD threat often decreases with geomagnetic latitude, the E3 HEMP threat is higher at lower geomagnetic latitudes due to its generation mechanism), engendering the real possibility of wide-area GIC-caused blackout with transformer and grid equipment failures (see "NERC TPL-007").

ORDER

Given the above circumstances, I have determined that it is necessary and in the public interest for the United States of America that all covered entities conduct a survey of covered equipment to determine vulnerabilities to GIC.

> Covered entities include every electric utility and electric project developer, owner and operator, regardless of ownership or operation by the public or private sector within the state, regardless of whether that utility is subject to the jurisdiction of the North American Electric Reliability Corporation (NERC), and regardless of the regional transmission operators or independent system operators with which it operates.

> Covered equipment includes all power transformers with primary voltage of 100 kV or greater and capacity of 25 MVA or greater and all Generator Step-Up (GSU) transformers with secondary voltage of 100 kV or greater and capacity of 25 MVA or greater

Based on my determination of an emergency set forth above, I hereby order:

A. Every covered entity shall conduct a technical assessment survey of all covered equipment within its jurisdiction to determine its vulnerability to geomagnetically induced currents, also known as ground induced currents (GICs), which are induced in the Earth by naturally occurring geomagnetic disturbances (GMDs) or the late-time (E3) component of high-altitude electromagnetic pulse (HEMP).

B. Specifically, covered entities shall use the analytic waveform plotted in Figure A.5 of "IEC 61000-2-9, Edition 2.0 2025-05" in their operating models to determine the susceptibility of their transformers to GICs associated with a peak magnetic field strength environment of 20,000 nT for E3 HEMP, which for a typical low conductivity ground conductivity in the United States will produce a peak electric field environment of 85 V/km, based on the recently updated International Electrotechnical Commission (IEC) international standard. (Evaluating the worst-case E3 HEMP threat to high voltage transformers and the grid will also consider severe GMD threats.)

C. Covered entities shall undertake GIC modeling under the assumption that their transformers are operating fully loaded at the time when the operating environment experiences the GIC insult utilizing the late-time E3 HEMP waveform in IEC 61000-2-9, Edition 2.0 2025-05.

D. Because the aging of power transformers increases their susceptibility to GIC due to degraded insulating oil condition and coil condition, covered entities shall consider the age of the transformers surveyed and de-rate those transformers according to ANSI/IEEE Standard C57.110 and IEEE Standard C57.91 when analyzing transformer susceptibility. After confirming and considering the age, condition, and loading of each transformer, the peak geoelectric operating environment (e.g. 85 V/km), and the ground conductivity profile, covered entities shall identify which transformers would be susceptible to the following effects: (a) Half-cycle saturation (b) GIC induced harmonics; (c) VAR consumption; and, (d) Generation of hot spots in

the core or structural elements, (e) oil or insulation degradation, and report the potential impacts of each variable's susceptibility to GIC.

E. No later than 180 days from the passage of this order, and while utilizing strict operational security for Critical Energy Infrastructure Information (CEII), covered entities shall provide a detailed report to (_Insert DOE Recipient__) with copies to their state's public utility commission, to the governor and appointed chief of homeland security, and to the state legislature.

F. The report shall contain the following data for all transformers and substations found to be susceptible to GIC based on the above survey parameters: (a) Transformer Brand (b) Transformer Place of Origin [nation where manufactured] (c) Transformer Design Specifications [i.e. windings and core configuration, winding impedances, winding DC resistances (specify whether assumed or measured), 1 phase vs. 3 phase, capacity (MVA), voltage (kV) (d) Transformer Age (e) Transformer Site Location [redacted for CEII] (f) Transformer Purpose [GSU, Auto, Step-down, Converter] (g) Replacement Lead Time and Replacement Cost.

G.   In addition to providing the above data in spreadsheet form, covered entities shall consider how to most expeditiously protect their transformers from GIC, based on the totality of the circumstances (design, purpose, age, replacement lead time, etc.).

H. Covered entities shall not consider "operating procedures" such as load shedding and VAR supply as sufficient forms of GIC protection since adverse GIC effects can occur rapidly (may be no warning with E3) and over large regions that overwhelm operational reaction capabilities, and procedures cannot block GIC from entering an operating electric grid.

I. The report shall also provide the following: (a) Recommended solutions to protect the grid against GIC by preventing or reducing the half-cycle saturation of transformers, (b) Total cost to implement GIC protection of all vulnerable transformers owned and operated by the covered entity and (c) a priority list of transformers considering individual transformer risk, transformers threat to the remaining grid if unprotected (half-cycle saturating and generating harmonics) and associated critical infrastructure/service loss.

J.   As part of this report, covered entities shall also provide their recommendations for funding the deployment of this GIC protection, which can include both government grant opportunities and rate recovery.

K. This Order shall be effective from _____ on _____, and shall expire at 00:00 AM EST on ____. Renewal of this Order, should it be needed, must be requested before this Order expires.

Issued in Washington, D.C. at _____.

_____
Chris Wright
Secretary of Energy

cc: FERC Commissioners
    Chairman Laura V. Swett
    Commissioner David Rosner
    Commissioner Lindsay S. See
    Commissioner Judy W. Chang

Exhibit M

Addendum on China, re: Secure the Grid Coalition's DOE "Speed to Power" RFI Response.
Secure the Grid Coalition. January 12, 2026.

January 12, 2026

U.S. Department of Energy
1000 Independence Ave, SW
Washington, DC 20585

Addendum on China, re: Secure the Grid Coalition's DOE "Speed to Power" RFI Response

Dear Department of Energy:

In response to DOE's "Speed to Power" RFI (2025-18058), our Secure the Grid Coalition[1] urged the Department to act aggressively to protect our nation's electric grid against threats which produce Geomagnetically Induced Currents (GIC) by rapidly deploying the capacitive neutral blocking device known as SolidGround® across the roughly 6000 transformers that are vulnerable to GIC.

This memorandum is an update to those recommendations, warning that foreign nations – including a major foreign adversary – are already taking that step.

Shortly after publishing our recent report "*Speed to Power on a Firm Foundation: Overcoming Dangerous Assumptions That Put America's Future at Risk*" we visited the EMPRIMUS manufacturing facility for SolidGround®, witnessing the final tests being performed on a unit that reached production completion. Those tests performed as designed, and the unit was packed into a shipping container bound for another country, albeit an allied nation, but not the United States of America.

More worrisome is the emerging evidence that the People's Republic of China (PRC) is beginning to employ this technology across its electric grid. Our "Speed to Power" report warned that "China has infringed upon the patents of the only proven viable neutral blocking device, the EMPRIMUS SolidGround® system, and is in production of these duplicate counterfeits, which are being deployed within China."

This warning was issued based upon ongoing patent trolling witnessed by EMPRIMUS starting in 2012 and the discovery in May 2022 that a major American technology company deploying data centers across China witnessed the Chinese grid operators installing what appeared to be counterfeits of the EMPRIMUS SolidGround® unit on large power transformers supporting those data centers.

For the PRC to counterfeit and deploy transformer protection technology across its own infrastructures while targeting our own for attack is in keeping with Chinese military warfighting doctrine, specifically *Unrestricted Warfare*.[2]

Recently, our Coalition became aware of additional evidence of China's increasing interest in deployment of the capacitive neutral blocking devices across the PRC grid – this time through a recent publication by Chinese researchers in an IEEE document associated with the 2023 8th Asia Conference on Power and Electrical Engineering (ACPEE) [979-8-3503-4552—0/23].

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[1] The Secure the Grid Coalition is a group of policy, energy, and national security experts dedicated to strengthening the resilience of America's electrical grid. It is sponsored by the Center for Security Policy, a 501(c)(3) nonprofit which receives no funding from governments, foreign sources, the electric industry, or any for-profit corporations involved in protecting the grid, including EMPRIMUS, which has developed the capacitive neutral blocking device known as SolidGround®

[2] *Unrestricted Warfare*, authored in 1999 by two PLA colonels, describes an attack sequence against a developed nation: secretly muster capital, strike financial markets, embed malware in computer systems, then paralyze "the civilian electricity network, traffic dispatch network, financial transaction network, telephone communications network, and mass media network" to trigger "social panic, street riots, and political crisis." The passage appears on pages 145-146. Thus, electric grid disruption is stated doctrine.

The document, titled "*Research Summary on Transformer DC Magnetic Bias and Suppression Technology*" discusses the risks of DC bias in transformers due to ground currents which enter the transformer neutral and can cause half cycle saturation, which greatly increases harmonics, current excitation and distortion, temperature increases, loss increases, and vibration intensification – threatening the safe operation of the transformer. Similar to the process the Department of Energy went through under EO 13744 analyzing technologies to protect transformers and prevent DC bias, this research paper indicates that China has gone through their own process and is focused on capacitive DC blocking devices as the solution.

On page 2718 of this paper, the Chinese researchers state the following:

> "*At present, most neutral grounding transformers of 220kV and above substations in China are mostly considered to install capacitor DC blocking devices*"

The paper provides schematic illustrations of the "capacitor DC blocking devices" as well as schematics showing the addition of a resistor in series with the capacitor, which are copies of the concepts and designs of SolidGround®.

China has modeled their grid and written extensively of their concerns of GIC on their power grid which causes "DC bias" in transformers. China EPRI as well as other state-run entities have ramped up their patent applications in China around "capacitive neutral blocking." While this paper addresses the issue of DC bias from ground current due to HVDC operation rather than GIC from solar weather or E3 HEMP, the above statement about the deploying of capacitive DC blocking devices on the neutrals of transformer of "220kV and above" (in addition to the installation of capacitive DC blockers in the neutral of transformers providing power to data centers), can be considered evidence that the Chinese are in fact taking steps to protect their transformers from DC ground currents, including GIC.

EMPRIMUS continues to spend most of its time working with foreign customers outside of China and the demand appears to continue increasing abroad for its SolidGround® technology, while the U.S. grid – which is much more susceptible than many of these other nations – remains vulnerable.

We therefore recommend DOE take urgent action to address the GIC threat through the rapid deployment of SolidGround®.

Finally, as a reminder, our Secure the Grid Coalition and its sponsor – the Center for Security Policy – refuses funding from foreign sources, governments, and corporations – such as EMPRIMUS – who can profit from our policy recommendations. We provide these recommendations purely in the public interest and we stand ready to assist DOE as needed in pursuit of our shared goals to Secure the Grid.

Respectfully Submitted,
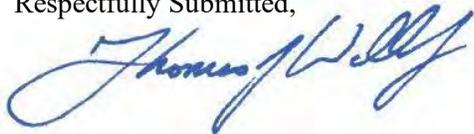
Lt. Col. Thomas J. Waller Jr. (USMC Ret.)
Co-Director
Secure-the-Grid Coalition
twaller@centerforsecuritypolicy.org
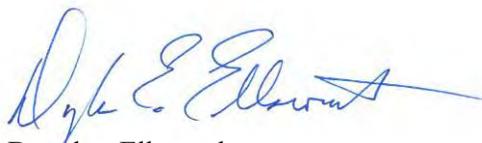
Douglas. Ellsworth
Co-Director
Secure-the-Grid Coalition
doug.ellsworth@usapact.org

Exhibit N

Executive Order 14318. "Accelerating Federal Permitting of Data Center Infrastructure." July 23, 2025.

Presidential Documents

Title 3—

The President

Executive Order 14318 of July 23, 2025

Accelerating Federal Permitting of Data Center Infrastructure

By the authority vested in me as President by the Constitution and the laws of the United States of America, it is hereby ordered:

Section 1. *Policy and Purpose.* My Administration has inaugurated a golden age for American manufacturing and technological dominance. We will pursue bold, large-scale industrial plans to vault the United States further into the lead on critical manufacturing processes and technologies that are essential to national security, economic prosperity, and scientific leadership. These plans include artificial intelligence (AI) data centers and infrastructure that powers them, including high-voltage transmission lines and other equipment. It will be a priority of my Administration to facilitate the rapid and efficient buildout of this infrastructure by easing Federal regulatory burdens.

In addition, my Administration will utilize federally owned land and resources for the expeditious and orderly development of data centers. This usage will be done in a manner consistent with the land's intended purpose—to be used in service of the prosperity and security of the American people.

Sec. 2. *Definitions.* For purposes of this order:

(a) "Data Center Project" means a facility that requires greater than 100 megawatts (MW) of new load dedicated to AI inference, training, simulation, or synthetic data generation.

(b) "Covered Components" means materials, products, and infrastructure that are required to build Data Center Projects or otherwise upon which Data Center Projects depend, including:

(i) energy infrastructure, such as transmission lines, natural gas pipelines or laterals, substations, switchyards, transformers, switchgear, and system protective facilities;

(ii) natural gas turbines, coal power equipment, nuclear power equipment, geothermal power equipment, and any other dispatchable baseload energy sources, including electrical infrastructure (including backup power supply) constructed or otherwise used principally to serve a Data Center Project;

(iii) semiconductors and semiconductor materials, such as wafers, dies, and packaged integrated circuits;

(iv) networking equipment, such as switches and routers; and

(v) data storage, such as hardware storage systems, software for data management and protection, and integrated services that work with public cloud providers.

(c) "Covered Component Project" means infrastructure comprising Covered Components, or a facility with the primary purposes of manufacturing or otherwise producing Covered Components.

(d) "Qualifying Project" means:

(i) a Data Center Project or Covered Component Project for which the Project Sponsor has committed at least $500 million in capital expenditures as determined by the Secretary of Commerce;

(ii) a Data Center Project or Covered Component Project involving an incremental electric load addition of greater than 100 MW;

(iii) a Data Center Project or Covered Component Project that protects national security; or

(iv) a Data Center Project or Covered Component Project that has otherwise been designated by the Secretary of Defense, the Secretary of the Interior, the Secretary of Commerce, or the Secretary of Energy as a ''Qualifying Project''.

(e) ''Project Sponsor'' means the lead sponsor providing financial and other support for a Data Center Project or Covered Component Project, as determined by the Secretary of Defense, the Secretary of the Interior, the Secretary of Commerce, or the Secretary of Energy, as appropriate.

(f) ''Superfund Site'' means any site where action is being taken pursuant to 42 U.S.C. 9604, 9606, or 9620.

(g) ''Brownfield Site'' means a site as defined in 42 U.S.C. 9601(39).

Sec. 3. *Encouraging Qualifying Projects.* The Secretary of Commerce, in consultation with the Director of the Office of Science and Technology Policy (OSTP) and other relevant executive departments and agencies (agencies), shall launch an initiative to provide financial support for Qualifying Projects, which could include loans and loan guarantees, grants, tax incentives, and offtake agreements. All relevant agencies shall identify and submit to the Director of OSTP any such relevant existing financial support that can be used to assist Qualifying Projects, consistent with the protection of national security.

Sec. 4. *Revocation of Executive Order 14141.* Executive Order 14141 of January 14, 2025 (Advancing United States Leadership in Artificial Intelligence Infrastructure), is hereby revoked.

Sec. 5. *Efficient Environmental Reviews.* (a) Within 10 days of the date of this order, each relevant agency shall identify to the Council on Environmental Quality any categorical exclusions already established or adopted by such agency pursuant to the National Environmental Policy Act (NEPA), reliance on and adoption of which by agencies (pursuant to 42 U.S.C. 4336 and 4336c) could facilitate the construction of Qualifying Projects.

(b) The Council on Environmental Quality shall coordinate with relevant agencies on the establishment of new categorical exclusions to cover actions related to Qualifying Projects that normally do not have a significant effect on the human environment. Agencies shall, for purposes of establishing these categorical exclusions, rely on any sufficient basis to do so as each such agency determines.

(c) Consistent with 42 U.S.C. 4336e(10)(B)(iii), loans, loan guarantees, grants, tax incentives, or other forms of Federal financial assistance for which an agency lacks substantial project-specific control and responsibility over the subsequent use of such financial assistance shall not be considered a ''major Federal action'' under NEPA. For purposes of this order, Federal financial assistance representing less than 50 percent of total project costs shall be presumed not to constitute substantial Federal control and responsibility.

Sec. 6. *Efficiency and Transparency Through FAST–41.* (a) The Executive Director (Executive Director) of the Federal Permitting Improvement Steering Council (FPISC) may, within 30 days of the date that a project is identified to FPISC by a relevant agency, designate a Qualifying Project as a transparency project pursuant to 42 U.S.C. 4370m–2(b)(2)(A)(iii) and section 41003 of the Fixing America's Surface Transportation Act (Public Law 114–94, 129 Stat. 1312, 1747) (FAST–41). Within 30 days of receiving such agency notification, the Executive Director may publish Qualifying Projects on the Permitting Dashboard established under section 41003(b) of FAST–41, including schedules for expedited review.

(b) In consultation with Project Sponsors, the Executive Director shall expedite the transition of eligible Qualifying Projects from transparency projects to FAST–41 ''covered projects'' as defined by 42 U.S.C. 4370m(6)(A). To the extent that a Qualifying Project does not meet the criteria set forth

in 42 U.S.C. 4370m(6)(A)(i) or (iii), FPISC may consider all other available options to designate the project a covered project under 42 U.S.C. 4370m(6)(A)(iv).

Sec. 7. *Streamlining of Permitting Review.* (a) The Administrator of the Environmental Protection Agency shall assist in expediting permitting on Federal and non-Federal lands by developing or modifying regulations promulgated under the Clean Air Act (42 U.S.C. 7401 *et seq.*); the Clean Water Act (33 U.S.C. 1251 *et seq.*); the Comprehensive Environmental Response, Compensation, and Liability Act (42 U.S.C. 9601 *et seq.*); the Toxic Substances Control Act (15 U.S.C. 2601 *et seq.*); and other relevant applicable laws, in each case, that impact the development of Qualifying Projects.

(b) The Administrator of the Environmental Protection Agency shall, consistent with the Environmental Protection Agency's statutory authorities, expeditiously identify Brownfield Sites and Superfund Sites for use by Qualifying Projects. As part of this effort, within 180 days of the date of this order, the Administrator of the Environmental Protection Agency shall develop guidance to help expedite environmental reviews for qualified reuse and assist State governments and private parties to return such Brownfield Sites and Superfund Sites to productive use as expeditiously as possible.

Sec. 8. *Biological and Water Permitting Efficiencies.* (a) Upon identification of sites by the Secretary of the Interior and the Secretary of Energy as described in section 9 of this order, the action agency, as identified through the process described in the Endangered Species Act (16 U.S.C. 1531–1544) (ESA), shall initiate consultation under section 7 of the ESA with the Secretary of the Interior, the Secretary of Commerce, or both with respect to common construction activities for Qualifying Projects that will occur over the next 10 years at a programmatic level. The Secretary of the Interior and the Secretary of Commerce shall utilize programmatic consultation to ensure timely and efficient completion of such consultation.

(b) Within 180 days of the date of this order, the Secretary of the Army, acting through the Assistant Secretary of the Army for Civil Works, shall review the nationwide permits issued under section 404 of the Clean Water Act of 1972 (33 U.S.C. 1344) and section 10 of the Rivers and Harbors Appropriation Act of 1899 (33 U.S.C. 403) to determine whether an activity-specific nationwide permit is needed to facilitate the efficient permitting of activities related to Qualifying Projects.

Sec. 9. *Federal Lands Availability.* (a) The Department of the Interior and the Department of Energy shall, after consultation with industry and further in consultation with the Department of Commerce as to the Project Sponsors to which relevant authorizations shall be granted, offer appropriate authorizations for sites identified by the Secretary of the Interior or the Secretary of Energy, as applicable and appropriate for the relevant uses, consistent with 42 U.S.C. 2201, 42 U.S.C. 7256, 43 U.S.C. 1701 *et seq.,* and all other applicable law.

(b) The Secretary of Defense shall, pursuant to 10 U.S.C. 2667 or other applicable law and as and when the Secretary of Defense deems it necessary or desirable, identify suitable sites on military installations for Covered Component infrastructure uses and competitively lease available lands for Qualifying Projects to support the Department of Defense's energy, workforce, and mission needs, subject to security and force protection considerations.

Sec. 10. *General Provisions.* (a) Nothing in this order shall be construed to impair or otherwise affect:

(i) the authority granted by law to an executive department or agency, or the head thereof; or

(ii) the functions of the Director of the Office of Management and Budget relating to budgetary, administrative, or legislative proposals.

(b) This order shall be implemented consistent with applicable law and subject to the availability of appropriations.

(c) This order is not intended to, and does not, create any right or benefit, substantive or procedural, enforceable at law or in equity by any party

against the United States, its departments, agencies, or entities, its officers, employees, or agents, or any other person.

(d) The costs for publication of this order shall be borne by the Department of Energy.
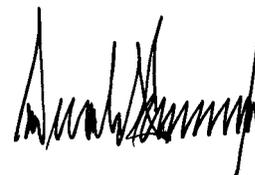
THE WHITE HOUSE,
July 23, 2025.

[FR Doc. 2025–14212
Filed 7–25–25; 8:45 am]
Billing code 6450–01–P

Exhibit O

"A New Threat to Power Grids: Data Centers Unplugging at Once: Dozens of data centers abruptly dropped off the power grid in recent Virginia incidents, forcing operators to take emergency action."
Wall Street Journal. March 1, 2026.

EXCLUSIVE | ENERGY & OIL | Follow

A New Threat to Power Grids: Data Centers Unplugging at Once

Dozens of data centers abruptly dropped off the power grid in recent Virginia incidents, forcing operators to take emergency action

By *Katherine Blunt* Follow *and* *Jennifer Hiller* Follow

March 1, 2026 5:30 am ET

Power-grid health is critical in Virginia, where data centers could use up to 57% of the state's electricity by 2030. JONATHAN ERNST/REUTERS

Early last year, a cluster of data centers in Virginia suddenly dropped off the power grid, threatening the stability of the already vulnerable system.

The roughly 40 data centers, which had been using enough electricity to supply more than one million homes, simultaneously switched to backup power sources in February 2025, when a high-voltage power line malfunctioned. The sudden plunge in electricity demand forced the grid operator to take quick action to avoid potentially serious damage.

The incident, details of which haven't been reported, was the second such problem in Virginia within a span of months. In July 2024, about 70 data centers withdrew from

the grid when another high-voltage line failed, requiring a similar scramble to keep power supply and demand in line.

Balancing the two is critical in maintaining the health of the grid: Both undersupply and oversupply of electricity demand can cause power plants to fail, resulting in blackouts and repair challenges. The issue is especially pressing in Virginia, where data centers are projected to use as much as 57% of the state's electricity by 2030.

In both instances, the loss in data-center demand totaled less than 2,000 megawatts —a substantial amount of power, but not enough to create a crisis for the grid operator, known as PJM Interconnection. PJM had operations in place to quickly reduce the amount of supply on the grid in response to the demand loss.

"It didn't cause an emergency, but I would say it caused concern," said Mike Bryson, PJM's senior vice president of operations. "What we're worried about is, what if that happens for 3,000 megawatts or 5,000 megawatts?"

Concerns about the rapid build-out of data centers often center on the risk that adding too many in a given region could strain electricity supplies, particularly on hot or cold days when demand is high. If demand threatens to exceed supply, grid operators call on power plants to ramp up production and, as a last resort, order utilities to cut power to customers to maintain balance.

Now, the opposite risk is emerging. Data centers are equipped with technologies that monitor for disturbances on the grid that could cause a power outage and affect operations. When disturbances occur, many data centers automatically shift to backup supplies, severing their grid connections until power quality stabilizes.

Both risks have been most acute within PJM, which operates a power market spanning 13 states from New Jersey to Kentucky. Home to the largest concentration of data centers in the world, PJM has for years been grappling with the prospect of electricity supply shortages as the enormous facilities use more and more power. The prospect of them disappearing unexpectedly causes more headaches for the grid operator.

The rapid build-out of data centers is raising concern as they could consume up to 17% of U.S. electricity by 2030, according to a new projection. KYLE GRILLOT/BLOOMBERG NEWS

Mark Christie, former chairman of the Federal Energy Regulatory Commission, last year requested a briefing on the risk of data centers tripping offline at once upon learning it had happened in PJM.

"I thought, 'Here is another threat to the reliability of the grid that we've got to get in front of,'" he said. "As we move into this era of massive load customers, the system is now at risk of being crashed from the load side."

As data centers use more electricity, the risk of serious disruptions resulting from their unexpected disconnection is mounting. The more demand drops at once, the more difficult it is for a grid operator to take enough supply offline to avert damage to power plants and other infrastructure.

Dominion Energy, a utility company that serves what is known as "data center alley" in Virginia, operates the power lines that were involved in each of the incidents that forced data centers offline there. It has been working with tech companies to determine how such facilities could stay online during brief faults on the system instead of switching to backup.

The risk is spreading outside PJM. The Texas grid operator, known as Ercot, has tracked cryptomining facilities unexpectedly tripping offline in recent years and is now trying to prevent that occurring with data centers as the state prepares for a surge in development. Ercot has estimated that if it lost more than about 2,600 megawatts of demand at once, the system would be at risk of failure.

Other new computing hot spots are emerging elsewhere in the U.S. Data centers could consume as much as 17% of U.S. electricity by 2030, up from 4% to 5% now, according

to projections released Thursday by the Electric Power Research Institute.

Although Virginia is the only state where data centers' share of electricity use currently exceeds 20%, that list could grow by 2030 to include states such as Arizona, Indiana, Iowa, Nebraska, Nevada, Oregon and Wyoming.

The North American Electric Reliability Corporation, a nonprofit tasked with monitoring the reliability of the U.S. power grid, is working with tech companies to figure out how to avoid sudden drops in data-center demand. NERC in February hosted a conference at which representatives from Google, QTS Data Centers and other companies discussed that challenge and others.

"It's one of our most important emerging risks," said Mark Lauby, NERC's senior vice president and chief engineer. "We're going to move faster, as fast as we can."

Appeared in the March 2, 2026, print edition as 'Power Grids' Newest Threat: Data Hubs Cut Off at Once'.

Katherine Blunt writes about Alphabet for The Wall Street Journal and is based in San Francisco. She previously covered power and utilities. Her coverage of PG&E was a finalist for the 2020 Pulitzer Prize for National Reporting and earned a Gerald Loeb award. She also shared a Loeb award for a special...

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Jennifer Hiller is a reporter covering the power industry from The Wall Street Journal's bureau in Houston. She writes on topics such as rising power demand, consumer energy costs, nuclear power, fusion, EV charging, renewables, electric reliability and the energy transition....

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Further Reading

The Fight Over Making Data Centers Power Down to Avoid Blackouts

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Videos

Exhibit P

**Electric Reliability Standards for Solar Geomagnetic Disturbances
Comments submitted to the Federal Energy Regulatory Commission
by Thomas S. Popik, George H. Baker, and William R. Harris.
June 2017**

Electric Reliability Standards for Solar Geomagnetic Disturbances

Comments submitted to the Federal Energy Regulatory Commission

by Thomas S. Popik, George H. Baker, and William R. Harris

July 2017

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

Electric Reliability Standards for Solar Geomagnetic Disturbances

Comments submitted to the Federal Energy Regulatory Commission

by Thomas S. Popik, George H. Baker, and William R. Harris

July 2017

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

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

The Commission completed its information-gathering in June 2017. The report was cleared for open publication by the DoD Office of Prepublication and Security Review on June 4, 2018.

This report is unclassified and cleared for public release.

July 2017

Dr. William R. Graham
Chairman
Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP)
Attack

Dear Dr. Graham:

As you have requested, the nonprofit Foundation for Resilient Societies, Inc. has approved the transmittal of that organization's documentary filing on a **Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events** as a Staff Report to the Congressionally-mandated EMP Commission.

This Staff Report was originally produced in July 2015 and then filed as corrected on August 10, 2015 in public Docket RM15-11-000 of the Federal Energy Regulatory Commission (FERC). The document provides a set of research findings and supporting evidence relating to the then-proposed NERC Standard TPL-007-1. This standard utilizes a benchmark model and a set of threat thresholds to assess the need for hardware protection of critical electric equipment within the U.S. bulk power system. Our docket filing expressed concerns that an overly-optimistic threat benchmark would result in no required hardware protection and therefore leave the U.S. electric grid vulnerable to solar storms. Had a higher and more uniform threat benchmark been established by NERC, Standard TPL-007-1 could have also provided a significant degree of protection against man-made EMP.

On September 22, 2016, FERC approved the proposed NERC Standard TPL-007-1 in FERC Order No. 830. Despite multiple requests for rehearing, FERC reaffirmed that standard in FERC Order No. 830-A on January 19, 2017.

Authors of the Staff Report to the EMP Commission dated August 10, 2015, comprising 91 pages, are Thomas S. Popik, Chairman of the Foundation for Resilient Societies, and two of the Senior Advisors to the later-reconstituted EMP Commission, Dr. George H. Baker and William R. Harris.

Respectful submitted by

William R. Harris
Senior Advisor

UNITED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

Reliability Standard for	)
Transmission System Planned Performance	) **Docket No. RM15-11-000**
for Geomagnetic Disturbance Events	)

<u>**COMMENTS OF THE FOUNDATION FOR RESILIENT SOCIETIES**</u>

Submitted to FERC on July 27, 2015
Corrected Comments submitted on August 10, 2015

Introduction

Pursuant to the Federal Energy Regulatory Commission's ("FERC" or "Commission") Notice of
Proposed Rulemaking ("GMD NOPR") issued on May 16, 2015,[1] the Foundation for Resilient
Societies ("Resilient Societies") respectfully submits Comments on the Commission's proposal
to approve the framework of Reliability Standard TPL-007-1 of the North American Electric
Reliability Corporation (NERC) as "just and reasonable," to approve specific requirements of the
standard, and to direct NERC to develop modifications to Reliability Standard TPL-007-1 and
submit informational filings.

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[1] *Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events*, Notice of
Proposed Rulemaking (NOPR), 151 FERC ¶ 61,134 (May 14, 2015) ("GMD NOPR"), 80 FR 29990 (May 26, 2015).

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Background

In FERC Order 779, FERC directed NERC to develop Second Stage Geomagnetic Disturbance (GMD) Reliability Standards:[1]

> The Second Stage GMD Reliability Standards must identify *benchmark GMD events* that specify what severity GMD events a responsible entity must *assess for potential impacts* on the Bulk-Power System. If the assessments identify potential impacts from benchmark GMD events, the Reliability Standards should require owners and operators to develop and implement a plan to protect against instability, uncontrolled separation, or cascading failures of the Bulk-Power System, caused by damage to critical or vulnerable Bulk-Power System equipment, or otherwise, as a result of a benchmark GMD event. (Emphasis added.)

As we will show in this comment, both the Benchmark GMD Event and the assessment criteria to identify potential impacts from the Benchmark GMD Event are fatally flawed. As a result, it is exceedingly unlikely that GMD Vulnerability Assessments by owners and operators will result in any significant protection against instability, uncontrolled separation, or cascading failures of the Bulk-Power System, except by voluntary action beyond the requirements of this standard.

Framework of Standard TPL-007-1
Overlapping Thresholds for Solar Storm Threat and Assumed Invulnerability of Transformers

The fundamental framework of Standard TPL-007-1 is defective because it overlaps a low solar storm threat or "Benchmark GMD Event," expressed in volts per kilometer, with a very high assumed invulnerability of transformers (also known as "Geomagnetically Induced Current (GIC) withstand rating") expressed in amps per phase. Only transformers having a lower withstand rating than the modeled GIC from the Benchmark GMD event would undergo "thermal assessment" to determine if hardware protection might be required.

If Standard TPL-007-1 were to use the same units of measure for both the assumed transformer invulnerability (GIC withstand rating) and the Benchmark GMD Event, it would be obvious that

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[1] *Reliability Standards for Geomagnetic Disturbances*, Docket No. RM12-22-000; FERC Order No. 779, 143 FERC ¶ 61,147 (May 16, 2013) ("FERC Order 779"), 78 FR 30747 (May 23, 2013), p. 2.

these limits have been imprudently set and are inconsistent with available real-world data. Unfortunately, the methodology implicit in the standard's framework is inherently difficult for the casual observer to understand, perhaps intentionally so. We can illustrate with an analogy to automobile crash testing.

For example, suppose the National Highway Traffic Safety Administration (NHTSA) asked automobile manufacturers to set a standard to determine if automobiles should have airbags installed as a protective measure against "high speed crashes." Further suppose that the NHTSA avoided a mandate to the industry by not specifying the miles per hour of a "high speed crash" but instead let the auto industry set this benchmark. Finally suppose that the NHTSA also let the auto industry determine a threshold limit for assumed resilience or invulnerability of cars and their occupants to crashes. For example, this threshold limit for assumed invulnerability to crashes might be 15 miles per hour.

As a first step, the automobile industry might propose a reasonable figure for a "high speed crash" by taking a survey of the radar gun readings on major highways to determine the upper speeds at which people actually drive. Using upper speeds, the resulting benchmark for a "high speed crash" might be quite substantial—for example, 75 miles per hour. If this were the "high speed crash benchmark," all cars would probably need airbags installed. As an alternative, if the auto industry were to average the speed of travel on all types of roads, the benchmark could be considerably lower—for example, 50 miles per hour.

In the analogous case of Standard TPL-007-1, if the Benchmark GMD Event were to be set at the maximum threat level that had been estimated by the respected space weather scientists previously engaged in the NERC standard-setting process (30-40 volts/kilometer), many transformers might need hardware protection. Instead, the NERC Standard Drafting Team, consisting all of industry representatives except for one scientist, downwardly averaged the Benchmark GMD Event to 8 volts/kilometer. And instead of using maximum readings of geomagnetic disturbances recorded in the United States, the NERC standard-setting team opted to use averaged data from Northern Europe over a limited time period lacking any major solar storms.

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Returning to the automobile airbag analogy, as a second step the industry might set a threshold limit for assumed invulnerability of cars and their occupants to crashes. Suppose in the absence of test data, this limit was initially set at 15 miles per hour. However, with the apparent goal of avoiding cost and redesign hassle of airbag implementation, further suppose the auto industry decided to reference tests of three automobile designs for crash resilience. After examining tests on *only three automobile designs*—the first test at 17 miles per hour, the second test without crash test dummies in the car and at 200 miles per hour, and the third test at speeds and conditions unavailable in a published paper or otherwise—the industry then extrapolated the results to determine that *every automobile design* would protect human occupants at crashes up to *75 miles per hour*.

In the analogous case of Standard TPL-007-1, the assumed invulnerability of transformers to damage from GIC was set in initial drafts of the standard at *15 amps per phase*. When industry representatives in the ballot body refused to vote in favor of a standard with this low GIC withstand threshold, the industry found tests on *only three transformer designs* and then extrapolated the results to conclude that *all transformer designs* are invulnerable to GIC up to *75 amps per phase*. Notably, none of the transformer tests referenced actually injected currents of 75 amps into a transformer under fully operational electrical load conditions—this asserted invulnerability to solar storms was based on paper studies using mathematical models.

Returning to the automobile airbag analogy, if the benchmark for a high-speed crash were set at 50 miles per hour and the assumed invulnerability of cars and their occupants to crashes were set at 75 miles per hour, then no cars would require airbags, because the vulnerability threshold (75 mph) exceeds the stress threshold (50 mph). The imprudent result would be obvious to the public—by personal real world observation, most people would know that cars commonly travel over 50 miles per hour and that passengers often die in crashes at speeds well below 75 miles per hour.

However, in the analogous case of Standard TPL-007-1, because the units for the solar storm threat and associated Benchmark GMD Event (in volts per kilometer) have been expressed differently than the units of assumed transformer invulnerability to GIC (in amps per phase),

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the imprudent result is not obvious to most casual observers. In fact, to make the units equivalent for comparison, one must have access to proprietary data of electric utilities and sophisticated modeling software.[2] Likewise, members of the public do not commonly observe GIC readings nor do they see transformers overheat and catch fire during solar storms.

In this docket comment, we will show that for nearly all transformers in two major networks, the modeled threat to large power transformers is below the assumed level of invulnerability. Moreover, we will show that purportedly invulnerable transformers in a major network, PJM Interconnection, have already experienced failure during solar storms far smaller than the Benchmark GMD Event.

Modeling of GIC Impacts

As utilities model their networks in advance of the standard's effective date and selectively release the results, it is becoming clear that the assumed transformer invulnerability to solar storms under the standard's "withstand rating" of 75 amps is almost always greater than the modeled GIC under the Benchmark GMD Event. As a result, the number of transformers needing thermal assessment under Standard TPL-007-1 would be trivial. It is also becoming clear that when networks are modeled using a more prudent benchmark event of 20 V/km and a more justifiable threshold for thermal assessment—for example, the "30 Amps At-Risk Threshold" in the FERC-sponsored Metatech-R-319 report[3]—significant numbers of transformers would need thermal assessment and potential hardware protection.

Below we present modeling results for three major networks: PJM Interconnection (PJM), Central Maine Power, and American Transmission Company (ATC). PJM modeling under the

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[2] The electric utility industry is in possession of GIC readings that would likely show the modelled GIC for the Benchmark GMD Event at particular transformer locations are below readings that have been already observed during smaller solar storms. However, GIC data that could expose the NERC standard as technically unjustified has been withheld from the standard-setting process, withheld from independent scientific study, and withheld from public view. For example, the Electric Power Research Institute (EPRI) has GIC readings from locations in the U.S. and Canada dating back to 1991, but nearly all of this data has been held as confidential and not used in NERC standard-setting.

[3] "Metatech R-319, Geomagnetic Storms and their Impact on the US Power Grid," John Kappenman, Metatech Corporation, Oak Ridge National Laboratory, January 2010, available at http://web.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-319.pdf, last accessed on July 26, 2015,

NERC Benchmark GMD Event shows only two transformers in their network would need thermal assessment.[4] Central Maine Power modeling shows that only one transformer out of 15 in their network would need thermal assessment under the NERC Benchmark GMD Event, but that 8 transformers, or 53%, would need thermal assessment under a 20 V/km benchmark event. ATC modeling shows that 24 out of 62 transformers, or 39%, would need thermal assessment under a 20 V/km benchmark event with a 30 amp "at-risk" threshold.

PJM System

As an example, we show modeling of estimated GIC for transformers during the benchmark solar storm within the PJM system spanning from Illinois to New Jersey. The modeling results below, presented by NERC Standard Drafting Team Chair Frank Koza, show that only two transformers in the PJM system have modeled GIC above the assumed transformer invulnerability of 75 amps.[5] Restated, only two transformers out of approximately 560 extra high voltage transformers within the PJM system would need vulnerability assessment—all other transformers within PJM would be assumed to be immune from GIC during the Benchmark GMD Event.

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[4] A third transformer is modeled at over 74 amps per phase, so effectively three of about 560 extra high voltage transformers in the PJM system need formal assessment under the proposed TPL-007-1 standard.

[5] "NERC GMD Reliability Standards," Frank Koza, PJM, Chair of NERC GMD Standard Drafting Team, INL Space Weather Workshop, Idaho Falls, ID, April 8, 2015, accessible at https://secureweb.inl.gov/gmdworkshop/pres/F_Koza_NERCGMDReliabilityStandards.pdf, last accessed July 26, 2015. The Frank Koza presentation is separately filed in this Docket as Resilient Societies' Reference Document No. 4.

Figure 1: Page 19 from presentation titled "NERC GMD Reliability Standards, Frank Koza, PJM, Chair of NERC GMD Standard Drafting Team, INL Space Weather Workshop, Idaho Falls, ID, April 8, 2015."[6]

As might be expected, PJM's modeling result is out of line with other published studies such as the Metatech R-319 study conducted by Oak Ridge National Laboratory and sponsored by FERC. The Metatech study showed approximately 330 transformers at risk, out of approximately 560 transformers in total, within the states of Pennsylvania, New Jersey, Delaware, Maryland, Virginia, West Virginia, Kentucky, Ohio, and Indiana, and Illinois that roughly overlay the PJM network.[7]

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[6] Area abbreviations are as follows: AEP is American Electric Power, DVP is Dominion, CE is ComEd, DEO&K is Duke Energy Ohio and Kentucky. Notably, PSEG, owner of the Salem 1 and 2 nuclear plants with failed transformers during GMD events, is not among PJM "Transformers with the highest GICs" and not above a mandatory transformer Screening Criterion.

[7] PJM transformer at-risk estimates developed from "30 Amp At-Risk Threshold" tables on pages 4-15 and 4-15 of "Geomagnetic Storms and Their Impacts on the U.S. Power Grid," Oak Ridge National Laboratory, available at http://web.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-319.pdf, last accessed on July 26, 2015, filed as a reference document on FERC Docket No. RM15-11-000.

Had the NERC Standard Drafting Team collected and analyzed GIC data for transformers within the PJM network, and transformers in other areas of the United States, these data would have shown that the Benchmark GMD Event and its associated scaling factors for latitude and ground models have been set to estimate GIC levels far below real world observations. In fact, the July 30, 2014 analysis of John Kappenman and William Radasky in the NERC standard-setting comment, "Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard," shows that real world GIC readings are two to five times higher than what the NERC ground model and latitude scaling factors in the Benchmark GMD Event would predict.[8]

Had the NERC Standard Drafting Team collected, analyzed, and disclosed failure data for all transformers within the PJM network, and for transformers in other areas of the United States, these data would have shown that multiple transformer failures have occurred during geomagnetic storms far smaller than the storm of the Benchmark GMD Event. According to NERC's own incident report, the Phase "A" and Phase "C" Generator Step Up (GSU) transformers at the Salem 1 nuclear plant in New Jersey failed during the 13 March 1989 solar storm.[9] The magnitude of the March 1989 storm was about one-quarter of the magnitude of the Benchmark GMD Event and one-fifth the magnitude of the 1-in-100 year event estimated in the Metatech R319 report. Yet these same transformers, modeled by PJM at less than 75 amps during the Benchmark GMD Event, are exempted from mandatory thermal assessment and any consideration of required hardware protection under the NERC-FERC proposed standard. By PJM modeling and NERC standard setting, the Salem 1 nuclear plant transformers have now become invulnerable to solar storms:

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[8] Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard," John Kappenman and William Radasky, Comment in NERC GMD Phase 2 Standard Setting, July 30, 2014.

[9] "March 13, 1989 Geomagnetic Disturbance," North American Electric Reliability Council, July 9, 1990, available at http://www.nerc.com/files/1989-Quebec-Disturbance.pdf, last accessed on July 26, 2015, p. 19.

**Figure 2: Melted Windings of Phase 1A Transformer at Salem Nuclear Plant
in New Jersey in Aftermath of March 1989 Solar Storm**
Source: Photo as displayed on page 2-29 of Metatech-R-319 Report

Central Maine Power

Because the NERC Standard Drafting Team set the Benchmark GMD Event at a fraction of observed data and because the assumed transformer invulnerability or "GIC withstand" is a high 75 amps, one would expect that only a few transformers might need protection under the requirements of the standard in other regions of the U.S. In fact, Central Maine Power (CMP) has modeled their system under the "NERC 1-in-100 year Benchmark" and found only one transformer in their whole network that would need assessment for solar storm vulnerability: the transformer at Chester, Maine.[10]

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[10] "2014 Maine GMD/EMP Impacts Assessment, A Report Developed for the Maine Public Utilities Commission," Central Maine Power Co., December 2014, available as a reference document, p. 26.

Effective GIC A/phase for Maine transformers		Degree Amp Max	4.53 V/km NERC 1 in 100 year Benchmark	14 V/km Study team assumed 1 in 50 year event	20 V/km Study team assumed 1 in 100 year event	23.5 V/km Study team assumed 1 in 200 year event	29 V/km Study team assumed 1 in 500 year event
2 winding delta - wye	Chester SVC 18/345 kV	162	76	235	336	395	487
	Yarmouth GSU 22/345 kV #4	144	49	152	217	255	315
	Keene Road GSU 115/345 kV	160	32	98	140	165	204
2 winding Auto Xfmrs	Orrington 345/115 kV #1	64	4	14	20	23	29
	Orrington 345/115 kV #2	64	4	12	17	20	25
	South Gorham 345/115 kV #1	60	1	3	5	6	7
	South Gorham 345/115 kV #2	60	12	36	51	60	74
	Mason 345/115 kV #1	111	6	20	28	33	41
	Macguire Road 345/115 #1	30	27	83	120	139	172
	Keene Road 345/115 kV #1	160	6	18	26	31	38
3 winding Auto xfmrs	Coopers Mill 345/115 kV #3	30	35	109	155	182	225
	Surowiec 345/115 kV #1	38	17	52	75	88	108
	Albion Road 345/115 #1	30	60	186	266	313	386
	Larrabe Rd 345/115 #1	135	48	149	213	250	308

Table 1: Effective GIC in transformers for variations in geoelectric field[11]

For a 20 V/km geoelectric field event in Maine, the CMP modeling shows that 8 transformers, or 53%, would need thermal assessment and potential hardware protection with a 75 amp threshold for thermal assessment. CMP's modeling result is consistent in end result with the Metatech R-319 study sponsored by FERC—the Metatech study also showed that 8 transformers would be "at risk" in Maine, albeit under the "30 Amp At-Risk Threshold" scenario.[12]

Just as we see discordance between modeled GMD impacts within the PJM system and transformer failures in the real world, we see also discrepancies between modeled risk and real-world data in Maine. GMD modeling of the Chester transformer by John Kappenman and

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[11] Ibid.

[12] FERC Commissioners should also take into account the total absence of NERC Benchmark GMD Event modeling of a "coastal effect" impacting transformers proximate to saline water bodies. Both the PJM and CMP transmission systems are subject to "coastal effects" that increase quasi-DC currents in coastal zone EHV transformers. See "Coastal Effect" Section of these comments, *infra.*

William Radasky, in their July 30, 2014 comment to NERC, estimates GIC of approximately 300 amps per phase during a severe solar storm of 5,000 nT/minute, four times the GIC that would be estimated using the NERC Benchmark GMD Event.[13]

The table below supplied by Central Maine Power shows real-world impacts within Maine over the past twenty-five years, including numerous equipment trips, which are inconsistent with the modeled result that only one transformer in Maine might need hardware protection. In fact, the disclosure by Central Maine Power shows GIC of up to 58 amps/phase during storms[14] that were a fraction of the GMD Benchmark Event.

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[13] **"Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard,"** John Kappenman and William Radasky, Comment in NERC GMD Phase 2 Standard Setting, July 30, 2014.

[14] CENTRAL MAINE POWER COMPANY; SMD ACTIVITY ARCHIVE; August 1991 to Present Dates" as presented to Maine State Legislature Joint Energy and Utilities Committee in March 2013, filed as a reference document on FERC Docket No. RM15-11-000. On June 21, 2001, the Central Maine Power SMD Activity Archive shows GIC of 173.4 amps in the neutral of the Chester, Maine transformer. To get amps per phase, this figure is divided by three for a result of 58 amps per phase.

CENTRAL MAINE POWER COMPANY
SMD ACTIVITY ARCHIVE
August 1991 to Present Date

(Chester SVC SUNBURST equipment in service since March of 91)

Storm Rating (Top 10)	Event Date	Chester SVC Transformer DC Neutral (A)	Storm Severity	Comments
1	3/13/89	N/A	Severe	Hydro Quebec Blackout – All Orrington caps trip; Yarm 4 and MY gen vars went over +300 MVAR each; Orrington caps would not close back in
	6/5/91	42.9	Major	Impacts to CMP unknown/not documented
	6/17/91	31.7	Major	Impacts to CMP unknown/not documented
	7/9/91	20.7	Moderate	Impacts to CMP unknown/not documented
	7/13/91	27.4	Moderate	Impacts to CMP unknown/not documented
	10/1/91	27.7	Moderate	Impacts to CMP unknown/not documented
	10/29/91	45	Major	Impacts to CMP unknown/not documented
	11/8/91	47	Major	Impacts to CMP unknown/not documented
	2/3/92	47.5	Major	Impacts to CMP unknown/not documented
	2/8-27/92	51.2	Major	Impacts to CMP unknown/not documented
	5/10/92	50	Major	Impacts to CMP unknown/not documented
	4/5/93	19.9	Moderate	Impacts to CMP unknown/not documented
	9/13/93	26.2	Moderate	Impacts to CMP unknown/not documented
	2/21/94	31	Major	Impacts to CMP unknown/not documented
	4/17/94	18	Moderate	Impacts to CMP unknown/not documented
	5/2/94	33.5	Major	Impacts to CMP unknown/not documented
	8/23/92	33.8	Major	Impacts to CMP unknown/not documented
	2/21/94	31	Major	Impacts to CMP unknown/not documented
	5/1/94	33.5	Major	Impacts to CMP unknown/not documented
	9/8/94	42	Major	Impacts to CMP unknown/not documented
4	5/4/98	74.3	Severe	2 caps tripped at Orrington; Orrington Bus @ 328kV
8	10/22/99	61.3	Severe	NKI
	1/28/00	-12	Minor	NKI
	2/12/00	-12	Minor	NKI
3	4/6/00	81.7	Severe	SVC filter banks trip; distribution customers UPS's not functioning properly in North Coastal areas
	5/24/00	52	Major	NKI
2	7/15/00	-76	Severe	MS2 declared by ISO; Orrington KC3 trip; 7kV swing on 345kv system; many Auto xfmr LTC operations
10	8/11/00	42.8	Major	Surowiec KC2 trip - no apparent reason other than due to GIC
9	9/17/00	-59.5	Major	NKI
	10/5/00	-28.4	Moderate	NKI
	12/00	N/A	N/A	Entire month of December saw constant minimal activity; nothing greater than 5A neutral peak and 4.1 6th harm peak but activity was present entire month

CENTRAL MAINE POWER COMPANY
SMD ACTIVITY ARCHIVE
August 1991 to Present Date
Chester SVC SUNBURST equipment in service since March of 91)

Storm Rating (Top 10)	Date	Chester SVC Transformer DC Neutral (A)	Storm Severity	Comments
6	3/30/01	76.2	Severe	MIS G1 trip but think it was due to faulty control board – no other evidence for trip
	4/11/01	-30.9	Major	NKI
	6/13/01	32.6	Major	May be an anomaly – one time spike with very little activity before or after spike
	6/21/01	173.4.222	Severe	May be an anomaly – one time spike with very little activity before or after spike
	6/25/01	<5		Spike of 6th harm and very little neutral current flowing
	9/30/01	19.3	Moderate	NKI
	10/21/01	-21.5	Moderate	NKI
7	11/5/01	63.6	Severe	NKI
5	11/24/01	89.9	Severe	Chester SVC filter banks trip
	4/17-18/02	-15.0	Moderate	NKI
	4/19-20/02	21.1	Moderate	NKI
	9/4/02	17.0	Moderate	NKI
	5/29-30/03	60.6	Severe	NKI; 5/29/03; Kp of 8
	10/24 to 11/5/03	-98.0	Severe	NKI; 10/29/03 Very large GIC flow but no impacts seen by CMP
	7/24-27/04	52.5	Major	NKI; 7/27/04
	11/7-10/04	-88.0	Severe	NKI; 11/9/04
	1/17-22/05	52.2	Major	NKI; 1/21/05
	5/15/05	83.1	Severe	NKI
	8/24/05	96.9	Severe	Chester SVC Filter banks tripped
	9/11/05	33.4	Major	NKI
	12/14-15/06	37.5	Major	NKI; 12/14/06
	1/11-13/08	12.1	Minor	NKI; 1/11/08 Associated with Kp of 6
	1/17-19/08	39.9	Major	NKI; 1/18/08 Associated with Kp of 6
	3/25-28/08	8.6	Minor	NKI; 3/27/08 Associated with Kp of 6
	4/20 to 5/1/08	14.9	Minor	NKI; 4/20/08 Associated with Kp of 6
	3/31/09	10.5	Minor	
	6/24-25/09	7.1	Minor	NKI; 6/25/09 Associated with Kp of 6
	4/5-7/10	18.6	Moderate	NKI; 4/5/10 Associated with Kp of 6
	6/4/11	5.0	Minor	NKI
	6/5-8/11	9.6	Minor	NKI; 6/8/11 Associated with Kp of 6
	8/5-6/11	11.1	Minor	NKI; 8/5/11 Associated with Kp of 7
	9/9/11	3.7	Minor	NKI; Associated with Kp of 6
	9/26-27/11	24.7	Moderate	NKI; 9/26/11 Associated with Kp of 7
	10/24-25/11	22.1	Moderate	NKI; 10/24/12 Associated with Kp of 6

12

CENTRAL MAINE POWER COMPANY
SMD ACTIVITY ARCHIVE
August 1991 to Present Date

Chester SVC SUNBURST equipment in service since March of 91)

Storm Rating (Top 10)	Date	Chester SVC Transformer DC Neutral (A)	Event Severity	Comments
	1/24-25/12	7.3	Minor	NKI; 1/25/12 Associated with Kp of 6
	3/7-9/12	13.6	Minor	NKI; 3/9/12 Associated with Kp of 7
	3/12-15/12	5.7	Minor	NKI; 3/12/12 Associated with Kp of 6
	4/23-24/12	6.1	Minor	NKI; 4/23/12 Associated with Kp of 7
	6/16-18/12	20	Moderate	NKI; 6/16/12 Associated with Kp of 6
	7/13-16/12	5.4	Minor	NKI; 7/15/12 Associated with Kp of 6
	9/5/12	3.8		NKI; Associated with Kp of 6
	9/30 to 10/1/12	7.1	Minor	NKI; 10/1/12 Associated with Kp of 7
	10/8-11/12	12.6	Minor	NKI; 10/11/12 Associated with Kp of 6
	10/11/12	12.6	Minor	NKI; Associated with Kp of 6
	10/13/12	2.8		NKI; Associated with Kp of 6
	11/16/12	37.9	Major	NKI; Associated with Kp of 6
	11/14/12	6.3	Minor	NKI; Associated with Kp of 6

- Event Severity class based on Chester SVC SUNBURST 2000 GIC Recording standards/criteria
    - Storm ratings are based on magnitude of both the transformer neutral and 6th harmonic currents as well as the effect the storm had on CMP's system
- N/A – Chester SVC recording instrumentation not installed at this time or data not available
- NKI – No Known Impacts to grid

Table 2: Real-world GMD impacts in Maine over past twenty-five years.

American Transmission Company

American Transmission Company (ATC), a large electric utility that operates high-voltage electric transmission for much of Wisconsin, performed GIC modeling of their system using PowerWorld™ software. Modeling results for a variety of geoelectric field scenarios were presented in February 2013 at a GMD Task Force meeting held by NERC.[15]

Under a "30 amp At-Risk Threshold" and 20 V/km and below geoelectric field scenarios, a large proportion of ATC transformers would need thermal assessment.[16] In fact, 30% of ATC auto-transformers would need thermal assessment. Sixty-seven percent of ATC member Generator Step Up (GSU) transformers would need assessment. In total, of 62 ATC transformers, 24 (39%) would need thermal assessment. Notably, these ATC model results are largely consistent with the Metatech R-319 study sponsored by FERC. The Metatech study showed 27 transformers in Wisconsin would be at risk under a 30 amp threshold, approximately 59% of MVA capacity at the time of the study.

When a less stringent 75 amp threshold is applied to the ATC model results for geoelectric fields 20 V/km and below, the number of transformers needing thermal assessment is far lower—only 19% of ATC transformers would need assessment; 13% of autotransformers and 19% of GSU transformers. And under a 75 amp thermal assessment threshold and 2 V/km geoelectric field scenario (2 V/km geoelectric field would approximate the Benchmark GMD event scaled to Wisconsin), zero transformers in the ATC network would need thermal assessment.

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[15] NERC GMD Task Force presentation "Geomagnetically Induced Current (GIC) What ATC is doing about it," excerpted from slide compendium "GMD Task Force Phase 2, Ken Donohoo, Task Force Chairman, In-Person Meeting, February 25-27, 2013, p. 16 of ATC presentation.
[16] The ATC GIC table is presented in "neutral amps" that combine currents from all three phases while the at-risk threshold for a single transformer would be "amps per phase." To make comparisons, the "30 amp At-Risk Threshold" scenario would need to be multiplied by a factor of 3 for a result of 90 amps in the neutral.

Hence, it should not shock FERC Commissioners that, with the NERC proposed hardware protection standard already submitted by NERC and under review by FERC, the owners of the generation facility within the ATC transmission system with the highest projected amps of GIC during a severe GMD event – NextEra Point Beach – opted not to purchase neutral ground blocking equipment or other protective equipment when installing a replacement 345 kV GSU transformer in the Spring of 2015.[17]

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[17] The new Siemens GSU transformer at Point Beach was installed without GMD hardware protective equipment during the Spring 2015 maintenance outage. A senior engineer of Next Era Juno Beach was a member of NERC's GMD Task Force and would have known that the NERC-proposed standard would exempt Point Beach from mandatory hardware protections. See "Summary GIC Table for ATC GSU transformers," *infra*, showing the Point Beach GSU transformer as having the highest magnitude modeled GIC for East-West geoelectric fields postulated at either 2400 nT/sec (sic nT/minute) or 4800 nT/sec (sic nT/minute).

345 kV Auto-Transformers	480 nt/sec storm		2400 nt/sec storm		4800 nt/sec storm	
	2V/km North	1V/km South	10V/km North	6V/km South	20V/km North	12V/km South
	N-S Field	E-W Field	N-S Field	E-W Field	N-S Field	E-W Field
Arcadian 345/138 #1	-0.7	-12.8	-3.3	-64.2	-6.5	-128.4
Arpin 345/138 #1	3.0	-4.2	15.0	-20.8	30.1	-41.6
Arrowhead 230/230 #1	30.9	-7.6	154.3	-38.1	308.7	-76.2
Arrowhead 345/230 #1	31.9	-25.5	159.6	-127.5	319.1	-255.1
Bain 345/138 #4	-2.2	3.1	-10.9	15.4	-21.9	30.7
Bain 345/138 #5	0.0	2.9	-0.1	14.3	-0.2	28.7
Columbia 345/138 #1	3.0	2.6	15.2	12.8	30.4	25.5
Columbia 345/138 #2	9.2	7.7	46.2	38.7	92.3	77.5
Columbia 345/138 #3	3.1	2.6	15.4	12.9	30.7	25.8
Dead River 345/138 #1	8.2	4.6	41.2	23.2	82.3	46.5
Dead River 345/138 #1A	9.8	5.5	48.9	27.6	97.9	55.3
Edgewater 345/138 #1	-0.2	23.3	-1.0	116.6	-2.0	233.3
Edgewater 345/138 #2	-0.2	21.8	-0.9	108.8	-1.8	217.5
Fitzgerald 345/138 #1	5.0	-23.5	-25.0	-117.7	-50.0	-235.4
Forest Junction 345/138 #2	12.8	1.4	64.2	7.1	128.3	14.1
Gardner Park 345/115 #1	-3.2	5.0	-16.2	25.1	-32.4	50.1
Gardner Park 345/115 #2	-3.2	5.0	-16.2	25.1	-32.5	50.3
Granville 345/138 #1	-18.5	1.8	-92.5	9.2	-184.9	18.4
Granville 345/138 #1	6.0	2.2	29.8	11.2	59.5	22.5
Kewaunee 345/138 #1	0.0	3.0	0.0	14.8	0.1	29.7
Kewaunee 345/138 #2	0.0	8.3	0.1	41.7	0.2	83.4
Morgan 345/138 #1	-10.5	12.4	-53.0	61.9	-105.9	123.8
N. Appleton 345/138 #2	5.1	-1.9	25.5	-9.3	51.0	-18.7
N. Appleton 345/138 #3	6.3	-5.8	31.7	-29.2	63.3	-58.4
N. Appleton 345/138 #1	9.4	-0.5	46.8	-2.7	93.6	-5.4
N. Madison 345/138 #1	-3.4	-5.1	-17.2	-25.4	-34.3	-50.8
N. Madison 345/138 #2	-3.4	-5.1	-17.2	-25.5	-34.5	-51.0
Oak Creek North 345/138 #1	-9.7	22.9	-48.6	114.7	-97.3	229.3
Oak Creek North 345/138 #2	-10.8	25.4	-53.8	126.9	-107.7	253.8
Oak Creek North 345/230 #2	-1.5	1.9	-7.4	9.7	-14.7	19.5
Oak Creek North 345/230 #1	-1.1	1.5	-5.7	7.4	-11.3	14.8
Paddock 345/138 #1	-4.6	-13.4	-22.9	-66.8	-45.8	-133.7
Plains 345/138 #1	14.5	-1.4	72.5	-6.9	145.0	-13.9
Racine 345/138 #1	-4.2	3.7	-21.2	18.7	-42.3	37.4
Racine 345/138 #2	-15.9	4.7	-79.5	23.7	-159.1	47.4
Rockdale 345/138 #1	1.7	2.3	8.4	11.3	16.7	22.6
Rockdale 345/138 #2	7.4	10.0	36.9	49.8	73.7	99.5
Rockdale 345/138 #3	5.1	6.8	25.3	34.2	50.6	68.4
Rocky Run 345/115 #1	-1.2	-0.8	-5.9	-4.2	-11.9	-8.4
Rocky Run 345/115 #2	-2.7	-1.9	-13.4	-9.6	-26.9	-19.1
Rocky Run 345/115 #3	-1.7	-1.2	-8.4	-6.0	-16.8	-11.9
Saukville 345/138 #1	17.0	29.6	85.0	148.2	170.0	296.4
South Fond Du Lac 345/138 #1	0.2	0.8	1.2	3.8	2.3	7.6
South Fond Du Lac 345/138 #2	0.2	0.7	1.1	3.7	2.3	7.4
Stone Lake 345/161 #1	-50.7	-22.8	-253.4	-114.0	-506.9	-228.1
W. Middleton/Cardinal 345/138 #1	7.9	-36.2	39.6	-181.0	79.3	-361.9
Werner West 345/138 #1	-28.1	-26.8	-140.7	-134.0	-281.5	-267.9

Summary GIC table for ATC auto-transformers

Summary GIC table for ATC member GSUs						
		480 nt/sec storm		2400 nt/sec storm		4800 nt/sec storm	
		2V/km North	1V/km South	10V/km North	6V/km South	20V/km North	12V/km South
345 kv GSU's	N-S Field	E-W Field	N-S Field	E-W Field	N-S Field	E-W Field
Columbia (WPL) 345/22 #1	49.1	-30.4	245.3	-152.0	490.6	-304.0
Columbia (WPL) 345/22 #1	49.5	-30.7	247.7	-153.5	495.4	-306.9
Cypress 345/35 #1	-19.9	-7.1	-99.5	-35.5	-198.9	-71.0
Edgewater (WPL) 345/22 #1	11.3	18.3	56.4	91.5	112.8	183.1
Edgewater (WPL) 345/22 #1	19.4	31.5	97.1	157.6	194.2	315.3
Gardner Park 345/19 #1	10.2	-20.7	50.9	-103.3	101.9	-206.7
Kewaunee 345/20 #1	19.0	30.8	95.1	154.0	190.2	308.0
Oak Creek North 345/25 #1	6.1	9.8	30.4	48.9	60.8	97.8
Oak Creek North 345/25 #1	6.3	10.2	31.6	50.9	63.2	101.8
Pleasant Prairie 345/24 #1	-12.2	4.2	-60.9	21.1	-121.8	42.2
Pleasant Prairie 345/24 #1	-12.1	4.2	-60.7	21.0	-121.3	42.0
Point Beach 345/19 #1	12.8	36.2	64.1	181.1	128.2	362.2
Point Beach 345/19 #1	14.5	36.4	72.7	182.2	145.4	364.3
SEC 345/18 #1	-19.0	0.3	-94.8	1.7	-189.5	3.3
SEC 345/18 #1	-18.8	0.3	-94.0	1.7	-188.0	3.3

Table 3: GIC values for Auto-Transformers and Generator Step-Up Transformers in the American Transmission Company network

Electric Grid Impacts during GMD Events

Resilient Societies compiled a list of significant electric grid impacts during GMD events. The impacts include transmission substations, HVDC links, and nuclear power plants. All impacts occurred during storms that were a fraction of the magnitude of the Benchmark GMD Event. The impact at the Seabrook nuclear plant in November 1998 was a vibration related event. The impacts were concentrated in areas where the coastal effect enhancement of GMD fields is operative and at higher latitudes. Nonetheless, two impacts occurred at lower geomagnetic latitude—the Contra Costa, California substation transformer failure and tripping of the Blackwater HVDC link.

As part of the standard-setting process, NERC should have requested data on electric grid impacts during solar storms from electric utilities. Had this been done, it would have likely shown that requirements and measures of the standard will not protect against GMD events lower than the Benchmark GMD Event. We ask the Commission to remand the standard for collection of relevant data on grid impacts during GMD events and incorporation of these data into the standard-setting process.

Significant Electric Grid Impacts During Geomagnetic Disturbance Events					
Storm Date	Electric Grid Facility	City	State	Impact	Source
03/13/89	Contra Costa Substation	Los Medanos	CA	Transformer failure	IEEE Survey
03/13/89	Maine Yankee Nuclear Plant	Wiscasset	ME	Transformer damage	Resilient Societies
03/13/89	Salem 1 Nuclear Plant	Lower Alloways Creek	NJ	Transformer failure	NERC 3/89 GMD Report
09/19/89	Salem 2 Nuclear Plant	Lower Alloways Creek	NJ	Transformer failure	NERC 3/89 GMD Report
03/24/91	Radisson-Sandy Pond HVDC	Radisson	Quebec	HVDC Trip	L. Bolduc article, 2002
04/29/91	Maine Yankee Nuclear Plant	Wiscasset	ME	Transformer fire	Resilient Societies
05/28/91	Radisson-Sandy Pond HVDC	Radisson	Quebec	HVDC Trip	Boteler, et.al article, 1998
10/27/91	Radisson-Sandy Pond HVDC	Radisson	Quebec	HVDC Trip	ORNL/Sub/90-SQS8
10/28/91	Blackwater HVDC Tie	Clovis	NM	HVDC Trip	ORNL/Sub/90-SQS8
10/28/91	Radisson-Sandy Pond HVDC	Radisson	Quebec	HVDC Trip	Boteler, et.al article, 1998
11/10/98	Seabrook Nuclear Plant	Seabrook	NH	Transformer damage	Pacific NW Lab Report
04/06/00	Chester SVC	Chester	ME	UPS Malfunctions	Central Maine Power
07/15/00	Hope Creek Nuclear Plant	Artificial Island	NJ	Downrating to 55%	NRC Power Reactor Status
11/24/01	Chester SVC	Chester	ME	SVC Trip	Central Maine Power
07/15/12	Seabrook Nuclear Plant	Seabrook	NH	Downrating to 68%	Reuters News Service

Table 4: Select Impacts of GMD on Electric Grid Facilities
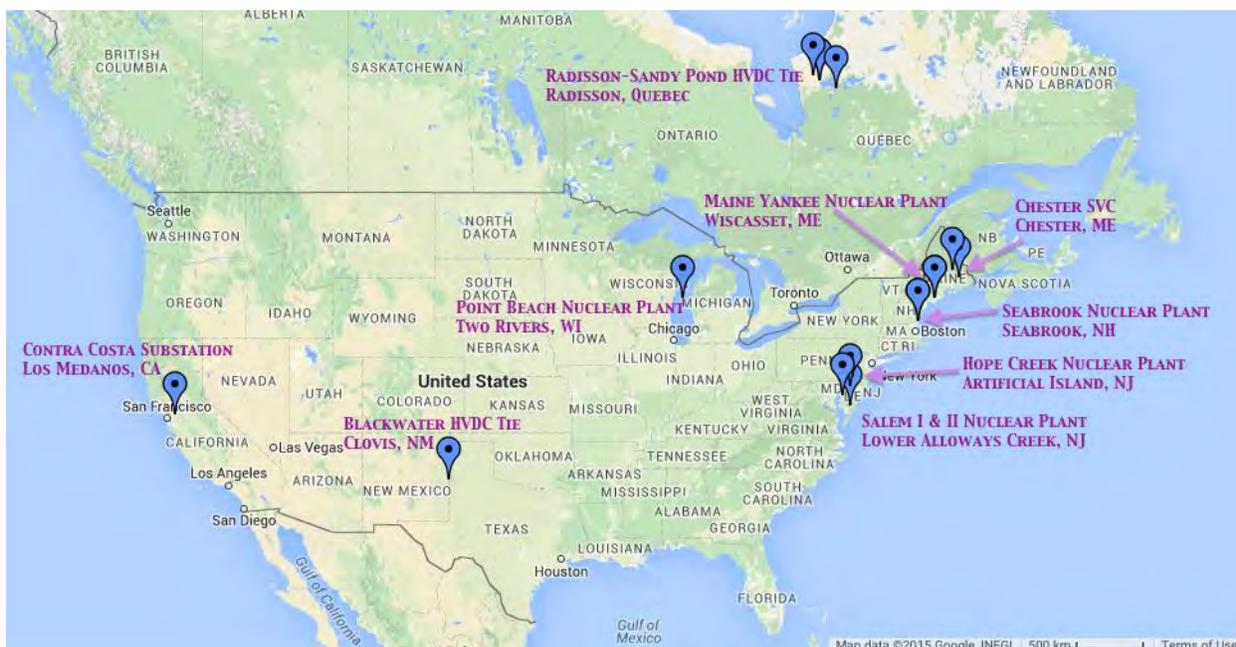
Figure 3: Select Locations of GMD Impacts on Electric Grid Facilities

Defects in Standard TPL-007-1

Technically Unjustified GMD Benchmark Event

In FERC Order 779, (p. 47):

> "71. In drafting the Commission ordered that benchmark GMD events be technically justified because responsible entities should not be required to assess GMD events (or protect against GMD events) "more severe" than the benchmark GMD (i.e., the rate of change in the GMDs magnetic fields), duration, geographic footprint of the GMD, how the GMD's intensity varies with latitude, system configuration, and the orientation of the magnetic fields produced by the GMD."

In FERC Order 779, (p. 2):

> "The Second Stage GMD Reliability Standards must identify "benchmark GMD events" that specify what severity GMD events a responsible entity must assess for potential impacts on the Bulk-Power System. The benchmark GMD events must be technically justified because the benchmark GMD events will define the scope of the Second Stage GMD Reliability Standards (i.e., responsible entities should not be required to assess GMD events more severe than the benchmark GMD events)."

The tolerant wording of this Commission order provided an incentive for NERC and members of the Standard Drafting Team to set a standard with a Benchmark GMD Event low enough for vulnerable transformers to escape mandatory hardware protection. As a regulatory body, it

should be the duty of the Commissioners to recognize this end-run around the intent of the Commission and to instead ensure a technically justified Benchmark GMD Event.

Fortunately, the wording of FERC Order 779 (p. 47) provides good detail on the factors to be considered in setting the Benchmark GMD Event, including but not limited to varying severity of the GMD (i.e., the rate of change in the GMDs magnetic fields), duration, geographic footprint of the GMD, how the GMD's intensity varies with latitude, system configuration, and the orientation of the magnetic fields produced by the GMD:

> 102. We recognize that there is currently no consensus on benchmark GMD events, and the Commission does not identify specific benchmark GMD events for NERC to adopt. Instead, this issue should be considered in the NERC standards development process so that any benchmark GMD events proposed by NERC have a strong technical basis.

In our specific comments below, we show how NERC and the Standard Drafting Team have been systematically imprudent in consideration of nearly every important factor, resulting in a Benchmark GMD Event without a "strong technical basis."

Severity of GMD in 1-in-100 Year Reference Storm

In the GMD NOPR (p. 21), the Commission appropriately recognized that geoelectric field values used in assessments should reflect the real-world impact of a GMD event:

> 35. The geoelectric field values used to conduct GMD Vulnerability Assessments and thermal impact assessments should reflect the real-world impact of a GMD event on the Bulk-Power System and its components.

However, in standard setting, NERC and the Standard Drafting Team assiduously avoided collecting and/or analyzing real world data from within the United States and Canada, including magnetometer readings from United States Geological Service (USGS)[18] and Natural Resources Canada observatories;[19] measured and estimated geoelectric field data in published sources;[20]

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[18] Natural Resources Canada has geomagnetic and geoelectric field data available for display and download at http://www.geomag.nrcan.gc.ca/plot-tracee/geo-i-en.php.

[19] USGS has geomagnetic data available for display and download at http://geomag.usgs.gov/products/.

[20] For an example of published work on GMD data and impacts back to 1847, see "The Effects of Geomagnetic Disturbances on Electrical Systems at the Earth's Surface - An Update," Boteler, David, et.al, 37th COSPAR Scientific Assembly. Held 13-20 July 2008, in Montréal, Canada. (2008) p.353.

and measured GIC data from EPRI,[21] government-owned utilities (such as Tennessee Valley Authority (TVA) and Bonneville Power Administration (BPA),[22] and private utilities (such as PSEG, the owner of the Salem 1, Salem 2, and Hope Creek nuclear plants).[23]

The Standard Drafting Team also avoided using real-world GMD impact data from a variety of sources, including published reports, the Licensee Event Report (LER) database available from the U.S. Nuclear Regulatory Commission, and the Generating Availability Data System (GADS) and Transmission Availability Data System (TADS) databases held by NERC itself. NERC contracted with Storm Analysis Consultants, Inc. for production of the report "An Analysis of the Equipment Vulnerability from Severe Solar Storms, Storm-R-112," (August 25, 2011) but this report has apparently been withheld from public disclosure by confidentiality agreement. Had NERC and the Standard Drafting Team collected and analyzed available real-world data, they would have likely found that the severity of GMD in 1-in-100 Year reference storm had been set far below a technically justified level and without "strong technical basis."

The Commission was right to propose in the GMD NOPR (p. 23):

> 38. Next, the record submitted by NERC and other available information manifests a need for more data and certainty in the knowledge and understanding of GMD events and their potential effect on the Bulk-Power System. For example, NERC's proposal is based on data from magnetometers in northern Europe, from a relatively narrow timeframe with relatively low solar activity, and with little or no data on concurrent GIC flows. Similarly, the adjustments for latitude and ground conductivity are based on the limited information currently available, but additional data-gathering is needed. To address this limitation on relevant information, we propose to direct that NERC conduct or oversee additional analysis on these issues.

When a NERC committee of respected space weather scientists estimated a reference storm in February 2013,[24] the "preliminary results" were determined to be a maximum geoelectric field

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[21] EPRI has operated its SUNBURST network of GIC monitors since 1991; see "Sunburst Network for Geomagnetic Currents" available at
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001023278.
[22] Resilient Societies has obtained GIC data from both TVA and BPA using the Freedom of Information Act. BPA currently publishes real-time GIC data on its website at
http://transmission.bpa.gov/business/operations/gic/gic.aspx.
[23] Resilient Societies requested GIC data from PSEG in 2011 and this request was declined.

of 30-40 V/km, as this slide from a contemporaneous presentation to the GMD Task Force presentation shows:[25]
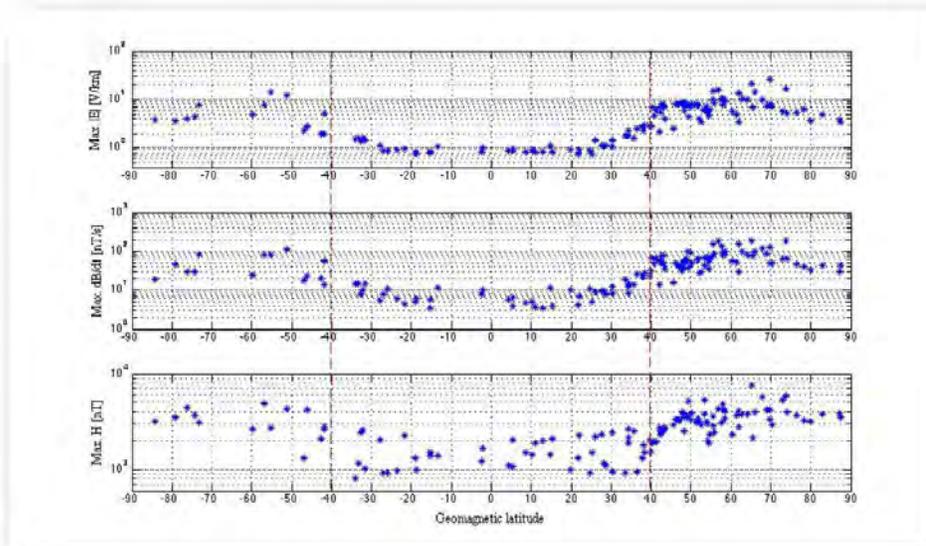
Figure 4: Slides from NERC GMD Task Force presentation

When GMD Task Force Team 3 initiated drafting of the "Application Guide" and gave a contemporaneous presentation in Vancouver in July 2013, the reference geoelectric field had been downwardly adjusted to a range between 5 V/km and 20 V/km. At this point the "Science

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[24] See presentation slides of "GMD Task Force Phase 2 Ken Donohoo, Task Force Chairman, In-Person Meeting, February 25-27, 2013", p. 52 and other relevant material available at http://www.nerc.com/docs/pc/gmdtf/MeetingSlides_25Feb_final.pdf . Space weather scientists on the "Current Science Team" at the time of the 30-40 V/km geoelectric filed estimate included A. Pulkkinen (NASA/CUA), W. Murtagh (NOAA), C. Balch (NOAA), J. Gannon (USGS), D. Boteler (NRCan), R. Pirjola (NRCan), D. Baker (U. of Colorado), and A. Thomson (BGS/EURISGIC).
[25] See "Response to NERC Request for Comments on Geomagnetic Disturbance Planning Application Guide," Resilient Societies, Comments to NERC GMD Task Force, August 9, 2013, filed as a record of standard-setting, p. 65

Working Group" of Team 3 consisted of only two scientist representatives, one from NASA/CUA and another from Oregon State University:[26]
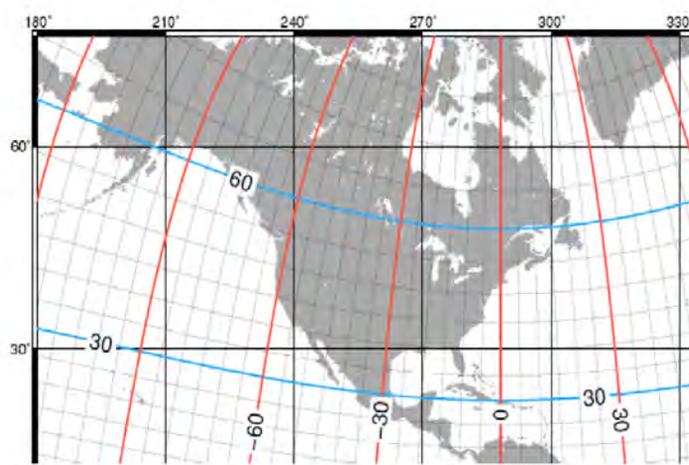
Figure 5: NERC Storm Scaling model slide

By April 2014, the Standard Drafting Team had set an even lower reference storm peak value of 5.77 V/km. approximately one fifth of the lower range preliminary estimate of 30V/km. At this time, only one scientist representative, an employee of the NASA Goddard Space Flight Center, remained on the Standard Drafting Team. The remaining team members were employed by

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[26] See "Team 3 Update, Application Guide Randy Horton, Southern Company, GMD Task Force Meeting, July 25, 2013" in the presentation slides for "GMD Task Force Phase 2, Ken Donohoo, Task Force Chairman, In-person meeting, July 25-26, 2013", available at
http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/presentations_all.pdf , p. 2, p. 4 and other relevant material.

PJM Interconnection, Southern Company, Georgia Transmission Corporation, Dominion Resource Services, NextEra Energy, Hydro One Networks, and American Electric Power.[27]

The apparent preference for a single scientist on the Standard Drafting Team, who might seek to espouse his own published hypotheses on spatial averaging of geoelectric fields, but not necessarily represent a scientific consensus on storm modeling, is not consistent with the "balancing" and "transparency" requirements of the Energy Policy Act and the NERC by-laws. In the aftermath of the October 2003 U.S.-Canadian Blackout, the primary purpose of developing reliability standards under Section 215 of the Federal Power Act is to *improve the reliability of the bulk power system;* this purpose is not achieved by use of unconfirmed scientific hypotheses.

In the final standard, the Standard Drafting Team set the reference peak geoelectric field to 8 V/km, upwardly adjusted from 5.77 V/km by an "implicit safety margin" of 25%. Given the storied history of the severity of GMD in 1-in-100 Year reference storm peak value, FERC was right to address this issue in the GMD NOPR:

> 36. To address this issue, the Commission proposes to direct NERC to develop modifications to the Reliability Standard so that the reference peak geoelectric field amplitude element of the benchmark GMD event definition is not based solely on spatially-averaged data. For example, NERC could satisfy this proposal by revising the Reliability Standard to require applicable entities to conduct GMD Vulnerability Assessments and thermal impact assessments using two different benchmark GMD events: the first benchmark GMD event using the spatially-averaged reference peak geoelectric field value (8 V/km) and the second using the non-spatially averaged peak geoelectric field value found in the GMD Interim Report (20 V/km).

However, it would be a mistake for FERC to determine that applicable entities might conduct two GMD Vulnerability Assessments, one at 8 V/km and another at 20 V/km, relying on the engineering judgment of the entities. Instead, FERC should order GMD Vulnerability

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[27] See "NERC Standard Drafting Team Rosters, May 2014,"available at http://www.nerc.com/pa/Stand/Documents/Standard_Drafting_Team_Rosters_March_2014.pdf , p. 21. The one remaining scientist from outside the electric utility industry espoused modeling based on Finland and other Northern European IMAGE geomagnetic sites; in lieu of modeling of the North American geomagnetic network and with GIC readings from North America. The foreseeable result is a proposal that FERC adopt a standard without a technical basis confirmed by scientific consensus.

Assessments at a single peak value set for technically justified protection of the public from solar storm blackouts. There cannot be two correct reference peak geoelectric field values; if there is doubt, FERC should mandate the higher value with greater safety for the public.

Geographic Footprint and Issue of Spatial Averaging

FERC had appropriate concerns about the use of spatial averaging to set the Benchmark GMD Event, proposing in the GMD NOPR (p. 24):

> 39. In particular, we propose to direct that NERC submit informational filings that address the issues discussed below. In the first informational filing, NERC should submit a work plan indicating how NERC plans to: (1) further analyze the area over which spatial averaging should be calculated for stability studies, including performing sensitivity analyses on squares less than 500 km per side (e.g., 100 km, 200 km); (2) further analyze earth conductivity models by, for example, using metered GIC and magnetometer readings to calculate earth conductivity and using 3-D readings; (3) determine whether new analyses and observations support modifying the use of single station readings around the earth to adjust the spatially averaged benchmark for latitude; and (4) assess how to make GMD data (e.g., GIC monitoring and magnetometer data) available to researchers for study. We propose that NERC submit the work plan within six months of the effective date of a final rule in this proceeding. The work plan submitted by NERC should include a schedule to submit one or more informational filings that apprise the Commission of the results of the four additional study areas as well as any other relevant developments in GMD research. Further, in the submissions, NERC should assess whether the proposed Reliability Standard remains valid in light of new information or whether revisions are appropriate.

The Benchmark Geomagnetic Disturbance (GMD) Event whitepaper authored by the NERC Standard Drafting Team proposed a conjecture that geoelectric field "hotspots" take place within areas of 100-200 kilometers across, but that these hotspots would not have widespread impact on the interconnected transmission system. Accordingly, the Standard Drafting Team averaged geoelectric field intensities downward to obtain a "spatially averaged geoelectric field amplitude" of 5.77 V/km for a 1-in-100 year solar storm. This spatially averaged amplitude was then used for the basis of the "Benchmark GMD Event".

Even the limited amount of publicly available GIC and magnetometer data shows the NERC "hotspot" conjecture is inconsistent with real-world observations and therefore the "Benchmark GMD Event" is not technically justified. Figures A and B below show simultaneous

GIC peaks observed at three transformers up to 580 kilometers apart, an exceedingly
improbable event if NERC's "hotspot" conjecture were correct.
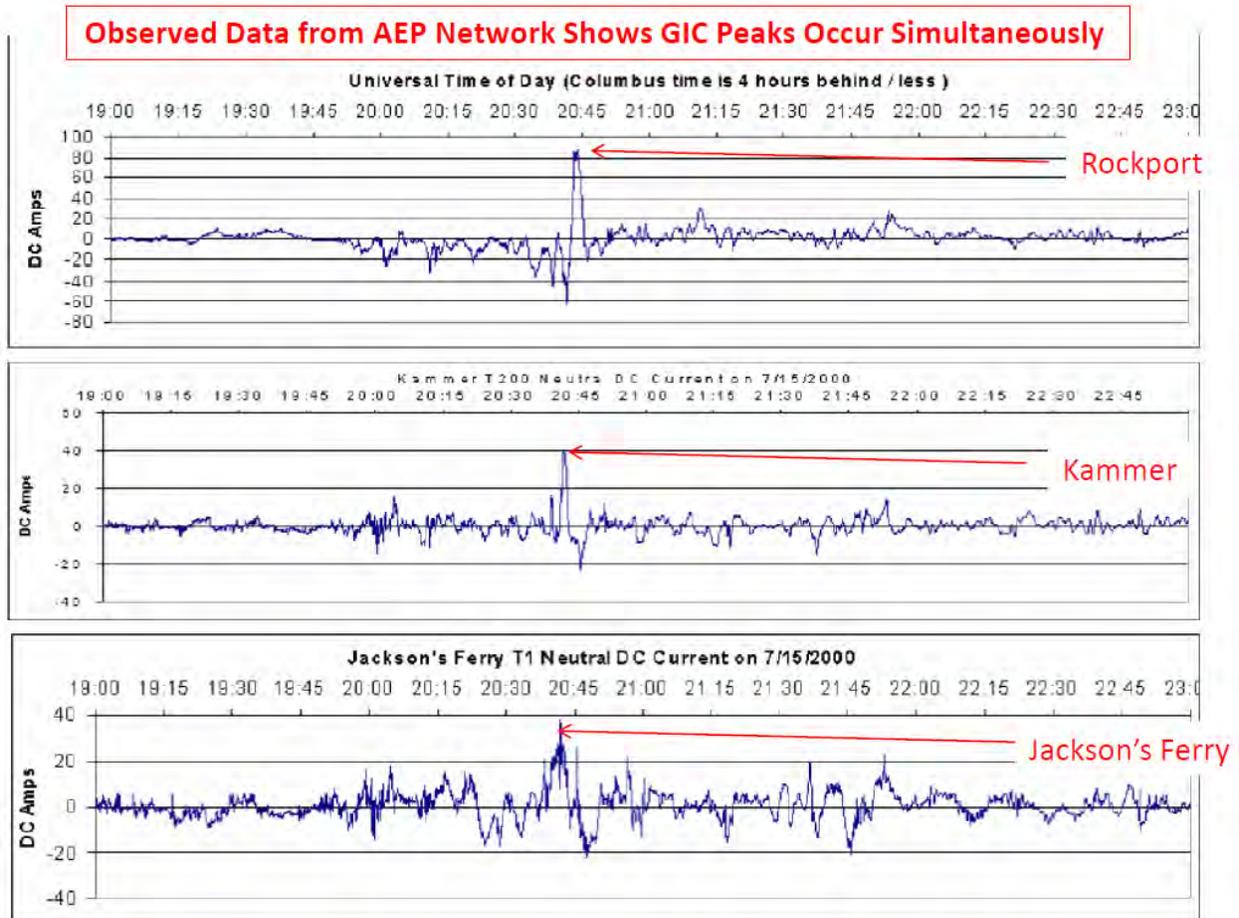
Figure 6: American Electric Power (AEP) Geomagnetically Induced Current Data Presented
at February 2013 GMD Task Force Meeting

Note: These three sites are all at the same 735-765kV level...this is excellent data.

Locations and Distances for GIC Peaks at Kammer, Jackson's Ferry, and Rockport Transformers
All Peaks Observed Simultaneously at ~22:42 Universal Time on July 15, 2000
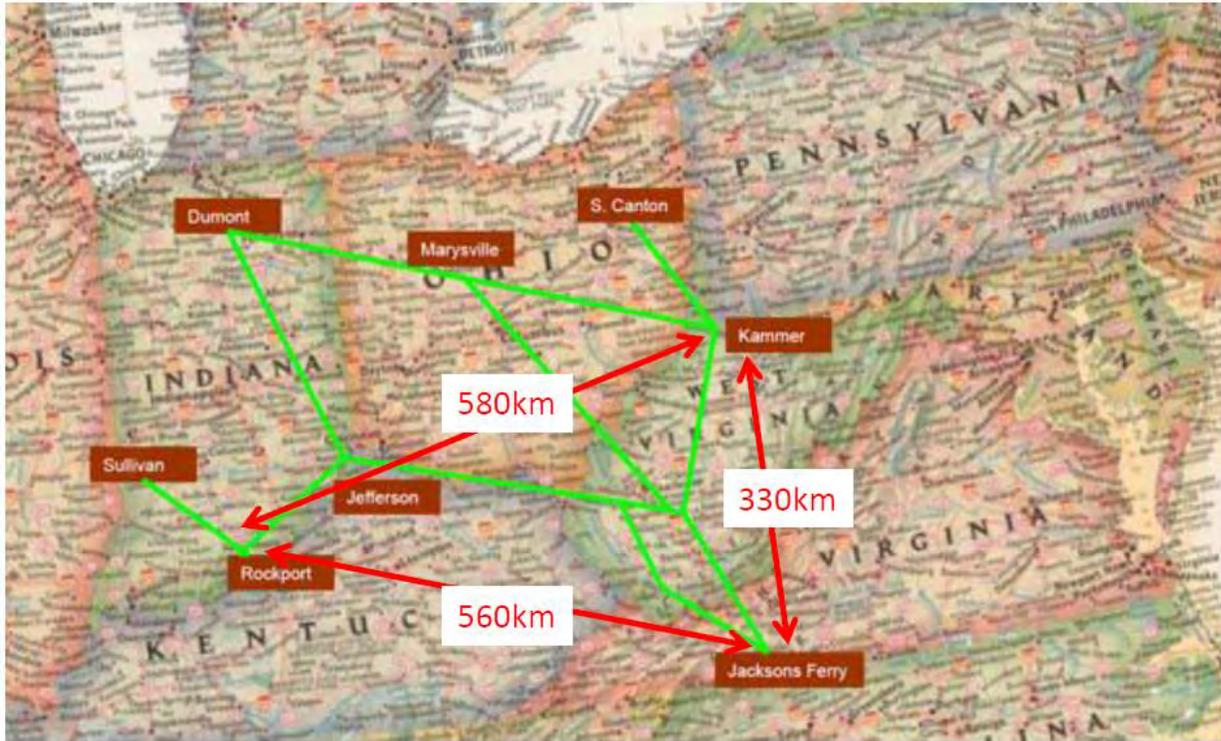
Figure 7: Location of Transformer Substations with GIC Readings on Map of States within AEP Network

According to Faraday's Law of induction, geomagnetically induced current (GIC) is driven by changes in magnetic field intensity (dB/dt) in the upper atmosphere. If dB/dt peaks are observed simultaneously many kilometers apart, then it would follow that GIC peaks in transformers would also occur simultaneously many kilometers apart, affecting reliable operation of the Bulk Power System.

Natural Resources Canada has a plotting service on their website where geoelectric fields for past storms are estimated at Ottawa and St. John observatories using dB/dt readings. Even cursory examinations of past solar storms show that peaks in estimated geoelectric field occur simultaneously at these two observatories 1,760 kilometers apart. Examples are presented below for three significant storms.

Simultaneous Geoelectric Field Troughs at 03:42 UT on 1991-03-24

Ottawa (OTT) based on 1-minute definitive data

St Johns (STJ) based on 1-minute definitive data
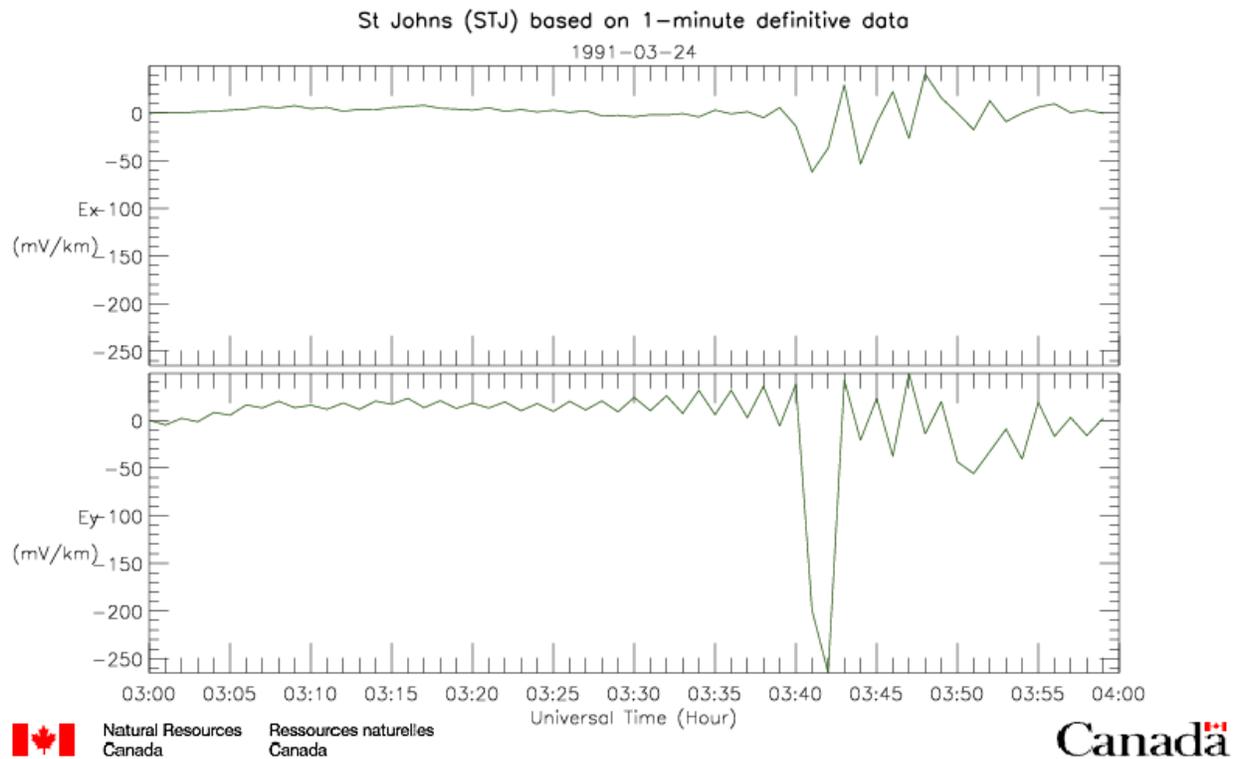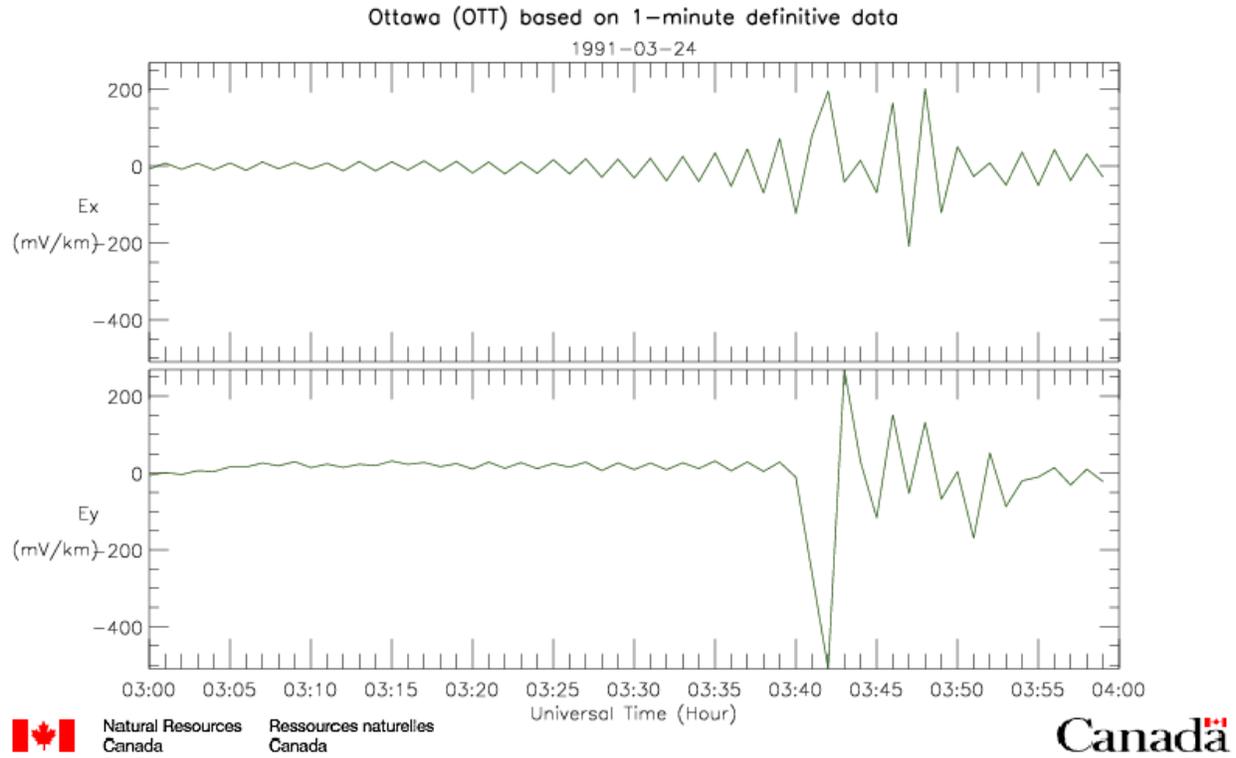
Simultaneous Geoelectric Field Peaks at 14:39 UT on 2000-07-15

Ottawa (OTT) based on 1-minute definitive data

St Johns (STJ) based on 1-minute definitive data
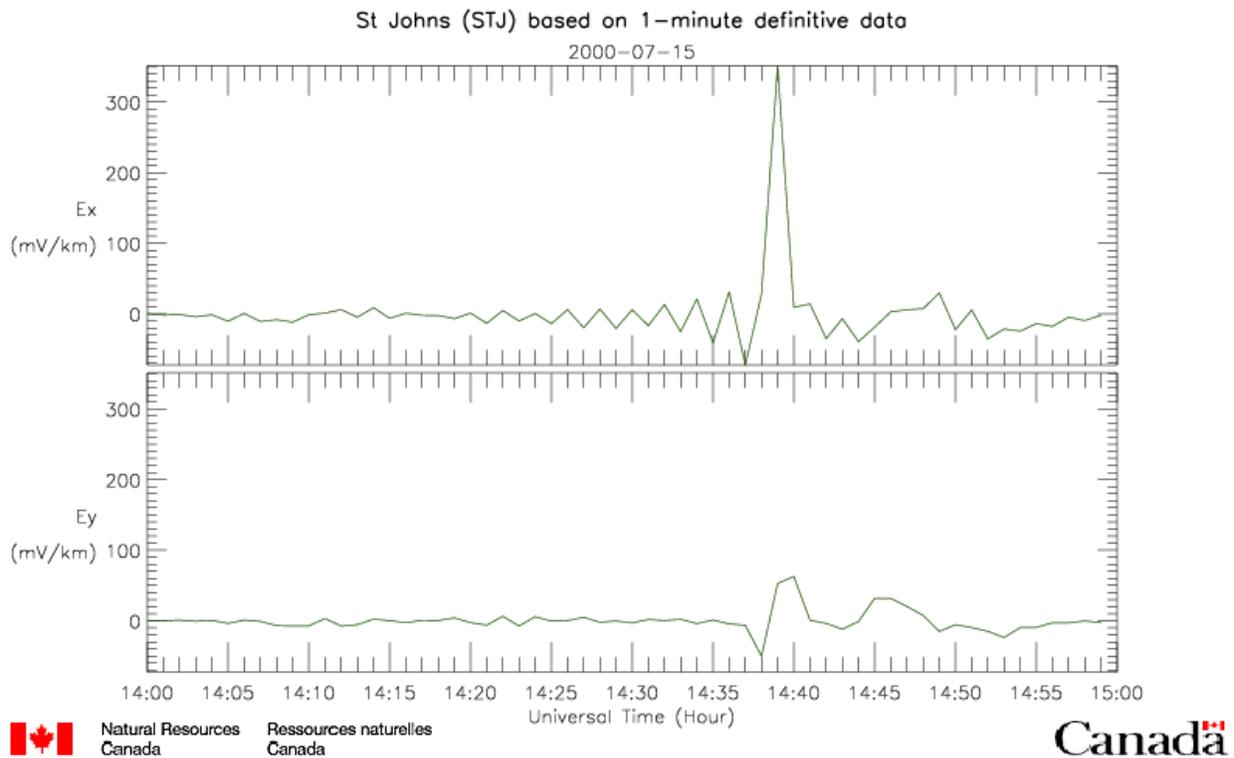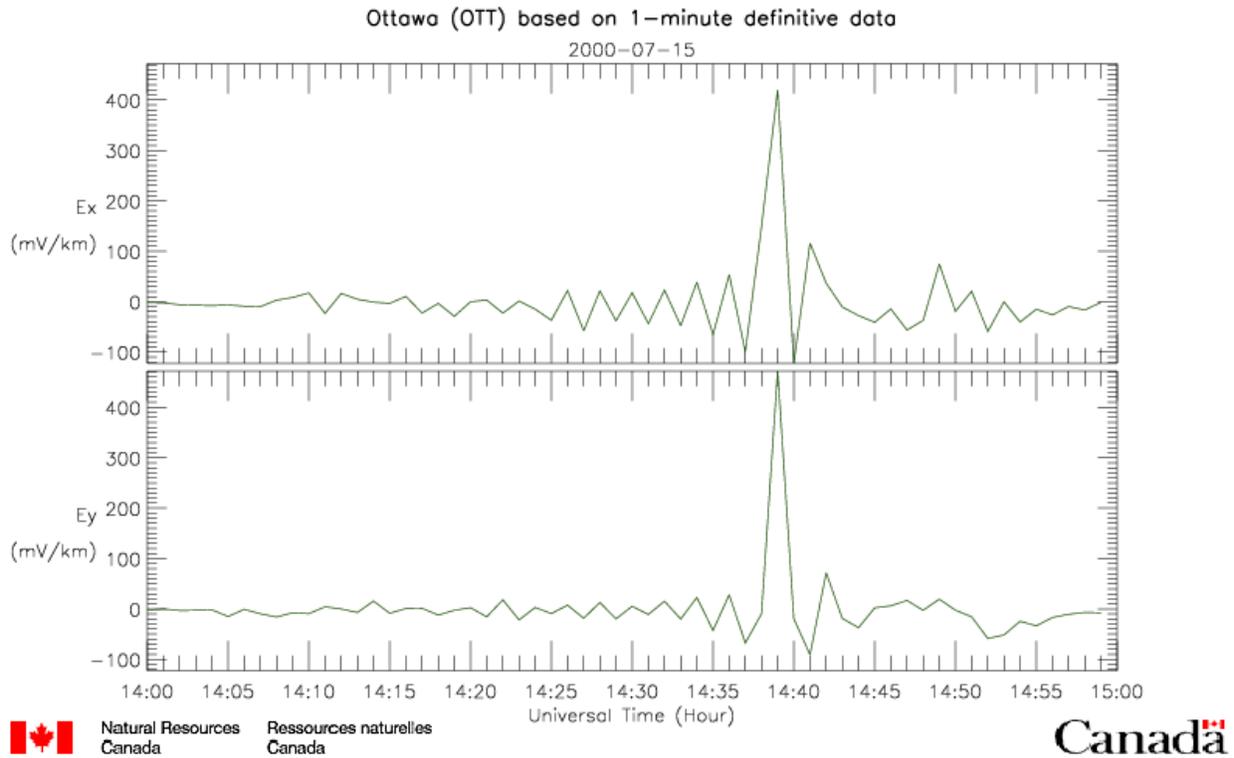
Simultaneous Geoelectric Field Troughs at 00:53 UT on 2001-03-31
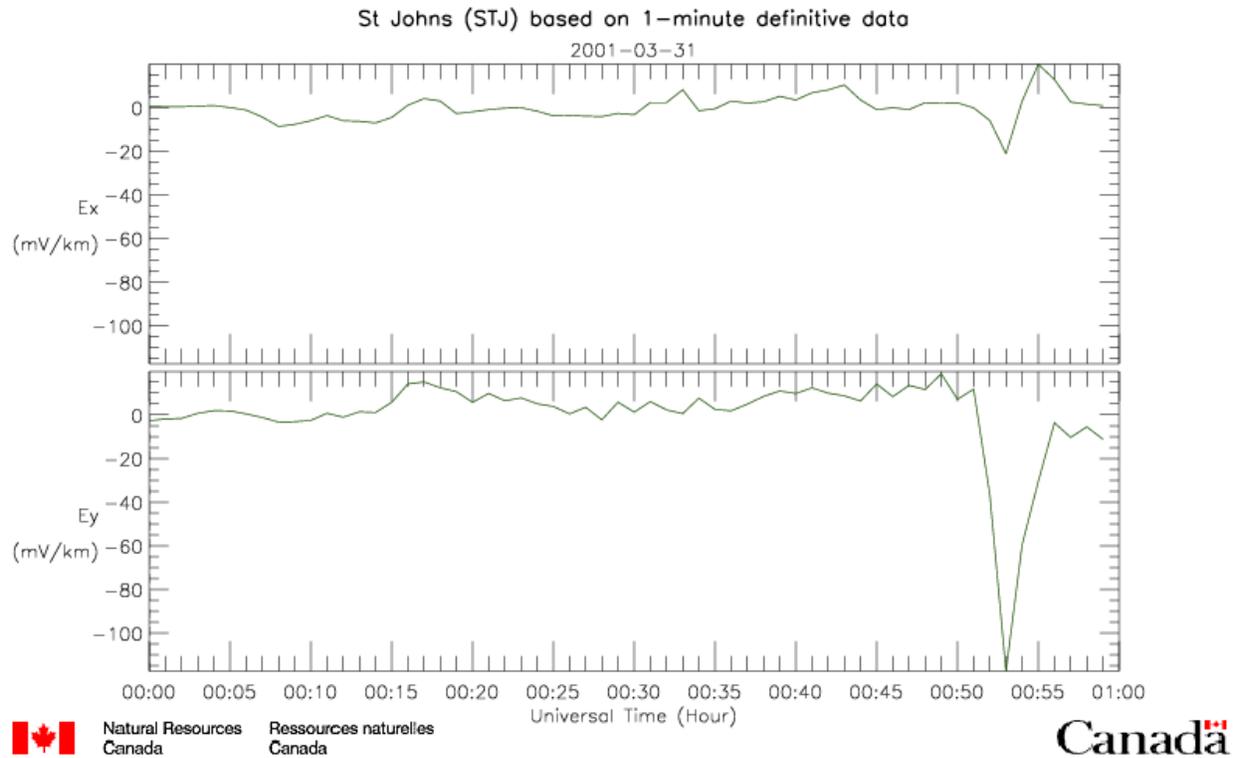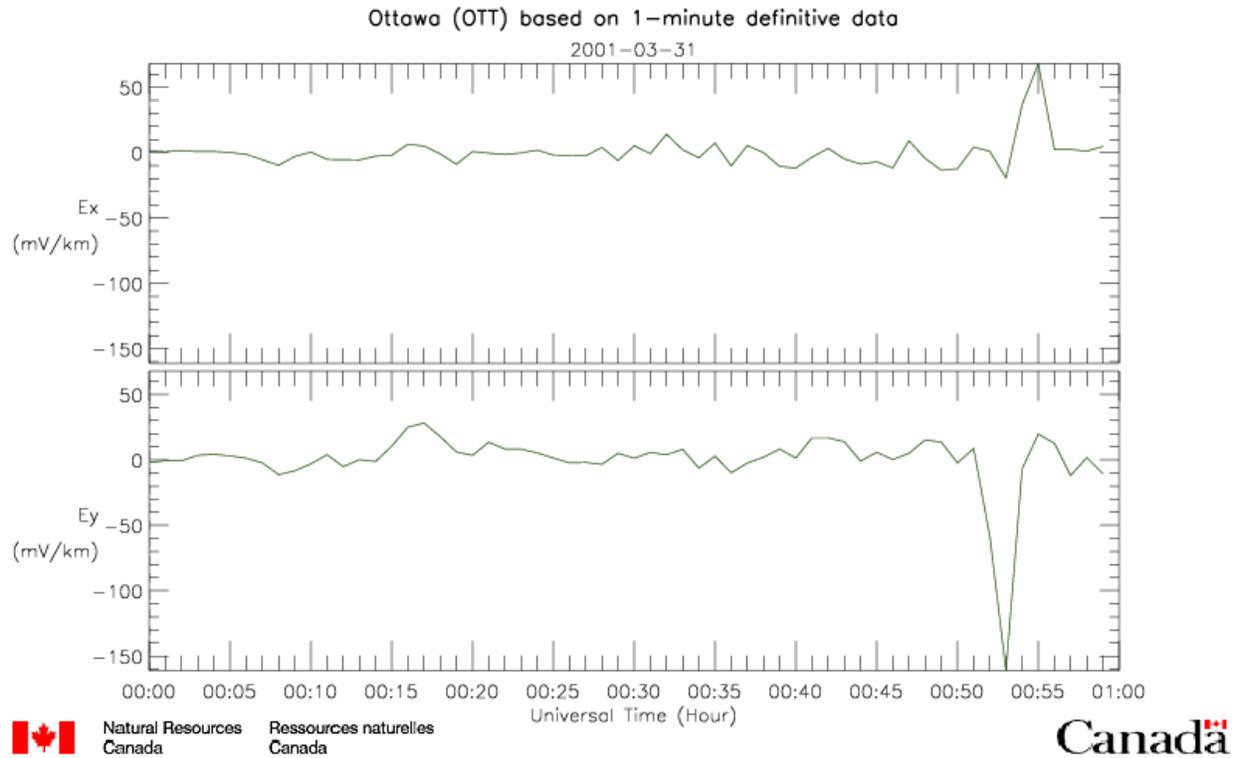
Figure 8: Synchronous Geoelectric field peaks and troughs in distant magnetometers

The weight of real-world evidence even now available shows the NERC "hotspot" conjecture to be erroneous.[28] Simultaneous GMD impacts can and do occur over wide areas. Greater collection and availability of GIC data at a variety of dispersed locations is likely to further confirm the NERC Benchmark GMD Event is technically unjustified and without "strong technical basis."

GMD Intensity and Variance with Geomagnetic Latitude

In the GMD NOPR (p. 23), the Commission appropriately recognized studies indicating that GMD events could have impacts on lower latitudes:

> "37. The Commission also seeks comment from NERC and other interested entities regarding the scaling factor used in the benchmark GMD event definition to account for differences in geomagnetic latitude. Specifically, the Commission seeks comment on whether, in light of studies indicating that GMD events could have pronounced effect on lower geomagnetic latitudes, a modification is warranted to reduce the impact of the scaling factors."

On FERC's own docket for the Stage 1 GMD Standard, there is a description of a transformer failure at a low-latitude location in Contra Costa, California due to GIC:

> It is widely known that the Salem Nuclear plant GSU transformer failure (due to winding heating) was caused by a combination of design of the transformer and its vulnerability to GIC-exposure. This was a Westinghouse manufactured single phase shell-form transformer. However, within the IEEE Survey, one other transformer failure during the March 1989 storm was also declared as being due to GIC. This had not been widely known and was overlooked until a careful review of the data in this survey was assembled in this report. This particular transformer failure was reported as being at the Contra Costa Bank 6 GSU transformer by Pacific Gas and Electric.[29]

Multiple published studies have demonstrated GMD impacts at low latitudes and levels of GIC below the thermal assessment threshold of 75 amps in the standard, including "Transformer failures in regions incorrectly considered to have low GIC-risk," "Storm sudden commencement events and the associated geomagnetically induced current risks to ground-based systems at

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[28] Resilient Societies had not as yet had time to analyze the Kappenman (Storm Analysis Consultants) and Birnbach (Advanced Fusion Systems) forensic review of how the GIC "hotspot" conjecture appeared, was then reformulated, and later surfaced with diminished justification for a new GMD Benchmark Event. The NERC ballot body may not have been fully informed and not enabled to understand before voting upon a standard for hardware protection lacking scientific consensus.

[29] "Comments of the John G. Kappenman, Storm Analysis Consultants," FERC Docket No. RM14-1-000, March 24, 2014.

low-latitude and mid-latitude locations," and "Geomagnetically induced currents in the Southern African electricity transmission network."[30,31,32] In light of this experience and published work, it would be imprudent and without "strong technical basis" for FERC to allow the aggressive geomagnetic latitude scaling factors of the Benchmark GMD Event.

Electric System Boundaries and Coastal Effects

Why does the model for the NERC Benchmark GMD Event systematically under-estimate geoelectric fields (volts per kilometer), or amps per phase, compared to empirical measurements? If a standard-seeking goal is to minimize the facilities and regions of the Bulk Power System that would be responsible to install hardware mitigation, then one tactic would be to eliminate entire classes of risks from benchmark modeling.

A candidate for NERC benchmark modeling that is conspicuously absent in the NERC standard is the coastal effect. The overall result of this purposeful exclusion is to down-rate modeled risks of solar storms in coastal regions of the Continental United States (CONUS) and Canada. Excluding the State of Alaska, fully 39 percent of the U.S. population resides in coastal counties that comprise just 10 percent of the landmass of the CONUS. These coastal counties with extended coastlines account for 48% of the Gross National Product of the United States. So the "coastal zone" is economically important.[33]

And the "coastal effect" or "coastal effects" play a significant risk-elevating role in scientific assessment of GMD vulnerabilities of the Bulk Power System, which has significant numbers of nuclear power plants and large load centers in the coastal zone.

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[30] "Transformer failures in regions incorrectly considered to have low GIC-risk," Gaunt, C.T., and G. Coetzee, Proceedings of Power Tech, July 15, 2007, Lausanne, Switzerland.
[31] "Storm sudden commencement events and the associated geomagnetically induced current risks to ground-based systems at low-latitude and midlatitude locations," John G. Kappenman, Space Weather, Volume 1, Issue 3, December 2003.
[32] "Geomagnetically induced currents in the Southern African electricity transmission network," Koen, J. and Gaunt, T., Power Tech Conference Proceedings, 2003 IEEE Bologna , vol.1, no., pp.7 pp. Vol.1, 23-26 June 2003.
[33] For an overview of the coastal economy, see the NOAA State of the Coast website, found at www.stateofthecoast.noaa.gov/coastal_economy/welcome.html.

Three sets of modeling considerations are intertwined when modeling the "coast effect." These are:

- **Edge effects of electric transmission systems**. Network modeling indicates that GIC tends to enter transmission systems from the edges; hence neutral ground blocking devices can be effective at these locations.
- **Boundary conditions associated with oceanic and land mass interactions**.
- **Higher conductivity of salt water adjacent to electric grid facilities**

The physical principles underlying these three interacting effects are described in published literature but not fully confirmed by empirical measurements. The so-called "coastal effect" was first identified as affecting electric grids nearly ninety years ago in Australia. Four geomagnetic storms recorded at seven separate observatories led to postulation of a "coastal effect" by the year 1926-27.[34] Albert Price advanced physics modeling of geomagnetic induction in 1973.[35] Thereafter, J. L. Gilbert of Metatech published in 1975 a model of interactions of geomagnetic storms at boundaries between oceans and landmasses. Gilbert estimated a coastal effect of about 2X compared to inland geoelectric fields.[36] Boteler and Prijola also published work on oceanic geoelectric fields.[37] Research on transoceanic cable systems modeled the so-called Dirichlet boundary condition, which has the effect of increasing GIC on the land side of various ocean-land boundaries. Some literature indicates that the "coastal effect" differs along different coasts and may relate to deeper subsurface magnetotelluric anomalies.[38]

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[34] Baird, H. F. "A preliminary investigation of some features of four magnetic storms recorded at seven observatories," M. Sc. Thesis, University of New Zealand, Canterbury College, Christchurch, 1927.

[35] Price, A.T., "The Theory of Geomagnetic Induction," T., "The Theory of Geomagnetic Induction," Physics of the earth and Planetary Interiors 7:227-233 (1973).

[36] Gilbert, J.L., "Modeling the effect of the ocean-land interface on induced electric fields during geomagnetic storms," Space Weather 3: S04A03 (1975).

[37] "Magnetic and electric fields produced in the sea during geomagnetic disturbances," Pure Appl. Geophys. 160: 1695-1716. (2003).

[38] See references 3, 4, and 5 in the U.S. Geological Survey submission of July 24, 2015 for additional references on the "coastal effect."

In the past two decades, measurement and modeling of the coastal effect that is also interrelated with end-of-line conditions has led to a broad range of estimates of impact upon the vulnerability of critical electric grid equipment.

At the high end of the range for "coastal effect" is the Atmospheric Environmental Research (AER) modeling performed for Lloyd's, in the context of an extensive electrical equipment claims database for North America that is not publicly accessible. The AER study asserts that the coastal effect increases exponentially near the coast.[39] Since claims data is likely to reflect the interactions of three variables (end of line effects; and ocean-land boundary effects, and ground conductivity), any model developed with the purpose of explaining empirical claims data may overstate the actual "coast effect" component.

More recently, Dr. David Boteler of Natural Resources Canada has participated in two reviews of the "coastal effect." One is a Chapter in a book (2014) under the editorship of Carol Schrijver on geomagnetic effects on the electric grid. This chapter cites a year 1987 study (Wannamaker) that estimates the coastal effect as being about a factor of 7.3X.[40]

In a study commissioned by the Electric Power Research Institute (EPRI), Dr. Boteler concluded in year 2013 that the best estimate for the "coastal effect" was a factor of 4X. Overall, we see estimates for the "coastal effect" and associated end-of-line and electric boundary effects between the range of 2X (Gilbert, 1975) and 7X (Wanamaker, 1987).

Finally, we should bring to the Commission's attention the significance of a careful statistical analysis of the Zurich Re claims database relating to the electric utility industry. This study does not specifically estimate a "coastal effect" but it may help to explain a key finding: unlike the NERC GMD Task Force and Standard Drafting Team, analysts of the Zurich Re insurance claims

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[39] See the Lloyd's-AER Report of June 2013, included as Reference Document No. 11. Sec. 5.3 at p. 10 states: "Coastal regions experience an enhancement in the surface electric field due to the high conductivity of seawater. This can be thought of as the seawater carrying extra charge, and the nearby, grounded, transformers provide a path for the current to flow. The enhancement from the coast effect increases exponentially towards the coast." Some "coastal counties" are shown on Fig. 4, indicating a relative risk factor for high risk counties as more than 1000X times low risk counties. "The regions with the highest risk are along the corridor between Washington, D.C. and New York City. Other high-risk regions are the Midwest and regions along the Gulf Coast." Lloyd's-AER Report at p. 10.
[40] See Reference Document No. No. 9, Dr. Boteler's chapter 4, cites Wannamaker (1987).

database which covers about 8 percent of electric utility insurance in the U.S. find no statistically significant relationship between geographic or geomagnetic latitude and the frequency and amount of insurance claims.[41] This one study casts serious doubt upon the validity of the so-called *Alpha factor* in the NERC Benchmark GMD Event model. Why is there no statistically significant correlation with geomagnetic latitude for the claims database? With a possible coastal effect of 2X to 7X, insurance claims along the Southeast Coast, the Florida Coast, and the Gulf of Mexico could counter or mask a smaller but valid *Alpha Factor.*

For public policy purposes, and for deciding whether to require hardware protective equipment for critical transformers in coastal zones, does it matter if there are three sets of physical principles that are difficult to untangle? If a NERC Benchmark Model exempts most every coastal zone facility, when empirical claims evidence indicates these facilities are at particularly aggravated risk of loss or damage, there may be reasons to require hardware protection, perhaps decades before physicists are able to sort out all the interactions of electric grid behavior in the coastal zone. [42]

Finally, it is notable that most of the transformer failures during moderate solar geomagnetic storms are within the "coastal zone" including: Maine Yankee in Wiscasset, Maine; Seabrook Station along the New Hampshire coast; and Salem-1 and Salem-2 nuclear power plants adjacent to Delaware Bay.

From the evidence adduced, it is apparent that it would be arbitrary and capricious for the Commission to approve the NERC Benchmark GMD Event model and associated standard elements without the consideration of a "coastal effect." Parties located near high-latitude coastal regions, such as Resilient Societies headquartered in New Hampshire and dependent on the Seabrook Station nuclear power plant, would be directly and materially affected by

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[41] See Schrijver, Dobbins, Murtagh, and Petrinec, in <u>Space Weather</u> (2014), Reference Document No. 13.

[42] A complication in this effort relates to the unavailability of some assessments of the "coastal effect" upon the transmission of electric currents from subsurface telecommunications cables that serve national security missions. Some of the best-instrumented ocean-to-land systems are telecommunication systems; these can show the attenuation in volts per kilometer as a cable extended from the near-coast to the interior, away from the coast. It is possible that FERC could seek technical assessment support from NSTAC, a National Telecommunications Advisory system that advises the President on national telecommunications requirements. An NSTAC Report on Telecommunications and Electric Power (2006) is included in Reference Document No. 14 in our filings.

omission of consideration of a coastal effect in the NERC standard and associated Benchmark GMD Event.

Vibration Effects at Lower GIC Thresholds than Thermal Effects

Another category of hazards to critical grid equipment is the effect of vibrations upon high voltage transformers. One aspect of vibration is known as *magnetostriction;* this effect can cause shaking and noise within high voltage transformers. Importantly, the vibrations occur at relatively lower magnitude geomagnetic storms than the magnitudes required to overheat high voltage transformers. Hence, in a severe solar geomagnetic storm, if vibrational effects are not modeled, the model may under-predict the percentage of critical equipment that is damaged or destroyed.

We first discovered an event that involved vibration effects and transformer damage by comparing a database of solar geomagnetic storms with Nuclear Regulatory Commission reports on transformer fires or losses. At Seabrook Station on November 8-9, 1998, there was a solar geomagnetic storm with a North-to-South storm overtaken by a South-to-North storm. These storm interactions can cause a "sudden impulse" even in a storm of moderate magnitude. A stainless steel bolt shook loose into the low voltage winding; and on Nov. 10, 1998, the low voltage windings melted; the transformer was shut down; and Seabrook Station had a 12.2-day outage.

First, Seabrook engineers claimed the damage could not have been caused by a solar storm, because the damage was at the low voltage winding, not the high voltage winding. Pictures of a Salem-1 transformer on March 13, 1989 also indicated the melted windings were at the low voltage end of the transformer. Next, Seabrook engineers claimed the loss was due to a mis-manufactured 4-inch stainless steel bolt. But why did the bolt stay in place for about 3000 days of transformer operation, and only fail during a sudden impulse GMD event?[43] Finally, the NERC

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[43] See Harris, "W.R. Seabrook Station Unit 1: Damage to Generator Step-Up Transformer Identified 10 November 1998 Immediately Following Geomagnetic Storm Shocks of November 7-9, 1998,"January 19, 2012, provided to NERC GMD Task Force January 2012, available at http://www.resilientsocieties.org/images/AD12-13-000_Resilient_Societies_Seabrook_Station_GMD_April_25_2012.pdf, last accessed July 27, 2015.

GMD Standard Drafting Team proclaimed this event was merely "anecdotal" as a basis to exclude the entire category of vibration hazards from the NERC Benchmark Model.

Where might non-anecdotal data be found to confirm that vibrational hazards are systematic and widespread during GMD events? The answer: NERC's own website, where the "March 13, 1989 Geomagnetic Disturbance" report published in 1990 identifies noise or vibration in at least seven separate locations during the 13 March 1989 solar storm.[44] Did NERC 's Standard Drafting Team cite their own report in considering vibrational impacts? They did not.

For references to an extensive theoretical and acoustical modeling literature on vibrational impacts on critical equipment, see Resilient Societies Level 1 Appeal documents of Jan 4-5, 2015.[45]

Finally, the GMD Task Force leadership attended experiments at Idaho National Laboratory (INL) in year 2013, together with officials from DTRA DOD and a member of the Resilient Societies' Board. For a science experiment that was purposeful and non-anecdotal, an INL Team supervised by Scott McBride injected DC power into a 138 kV transformer, and observed the vibration of the transformer; when power was off, the vibrations ceased. Then INL staff attached a neutral ground blocker. When the blocker was turned on, the vibrations ceased; when the neutral ground blocker was turned off, the vibrations returned.

In December 2013, Mr. McBride commented on the recent experiment showing vibration effects on an unprotected transformer, and the protections afforded by neutral blocking devices. Mr. McBride remarked: "Watching a 150,000-pound transformer visibly vibrating and

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[44] See 1990 NERC Compilation on March 13, 1989 Geomagnetic Disturbance at p. 57ff: Event 5 Noise SC Edison, Bishop, CA; Event 19, Noise, PJM Calvert Cliffs; Event 66, Noise PJM Calvert Cliffs; Event 77, Noise Portland GE, Oregon; Event 84, Noise PJM Calvert Cliffs; Event 90, Noise SC Edison Mira Loma; Event 105, Noise BPA Rose substation; Event 114, Nose WEP Point Beach, WI.
[45] For multiple references on vibrational models and vibrational impacts, readers should utilize click-through to the NERC Level 1 and Level 2 Appeals files, in Reference Document No. 5, submitted with this Comment filing.

moving along the ground during a simulated solar event (ground-induced current) is a sobering sight."[46]

Altogether, vibrational impacts are important components of GMD hazards to high voltage transformers. The Commission should remand the NERC standard to include, among other considerations, vibrational impacts and options for protective equipment against vibration.

Geomagnetic Field Orientation

The Commission sought comment from NERC in the GMD NOPR on geomagnetic field orientation (p. 27):

> The Commission seeks comment from NERC as to why qualifying transformers are not assessed for thermal impacts using the maximum GIC-producing orientation. NERC should address whether, by not using the maximum GIC-producing orientation, the required thermal impact assessments could underestimate the impact of a benchmark GMD event on a qualifying transformer.

We also wish to comment that GMD Vulnerability Assessments should contain a case for "maximum geomagnetic field orientation" and that any studies of transformer vulnerability, harmonic production, reactive power consumption, voltage collapse, equipment tripping, vibration impact, and other Bulk Power System vulnerabilities should be conducted using amperage from the maximum orientation.

Technically Unjustified Transformer Assessments
Screening Criterion for Transformer Thermal Impact Assessments

The GMD NOPR (p. 25) recites Reliability Standard TPL-007-1, Requirement R6, which proposes that transformers with an effective GIC of less than 75 A per phase during the Benchmark GMD Event would be exempt from thermal screening:

> Proposed Reliability Standard TPL-007-1, Requirement R6 requires owners of transformers that are subject to the proposed Reliability Standard to conduct thermal analyses to determine if the transformers would be able to withstand the thermal effects associated with a benchmark GMD event. NERC states that transformers are exempt

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[46] See Keith Arterburn, "Advancing a National Electric Grid Reliability Test Bed," Idaho National Laboratory, at https://inlportal.inl.gov/portal/server.pt/community/newsroom/257/feature_story_deeetails/1269?featurestory=DA_607328.

from the thermal impact assessment requirement if the maximum effective GIC in the transformer is less than 75 A/phase during the benchmark GMD event as determined by an analysis of the system. NERC explains that "based on available power transformer measurement data, transformers with an effective GIC of less than 75 A per phase during the Benchmark GMD Event are unlikely to exceed known temperature limits established by technical organizations.

The 75 amp per phase Screening Criterion for transformer thermal impact assessment is perhaps the most egregious defect in all of Standard TPL-007-1, as this important limit is almost entirely without technical basis. We took the time to carefully review the NERC whitepaper "Screening Criterion for Transformer Thermal Impact Assessment," as well as the key references, and we trust that FERC technical staff will re-review these documents after reading our comment. Here is a partial list of major defects in the Screening Criterion:

1. The Screening Criterion is a mathematically modeled construct without actual testing of any transformers under full load at 75 amps injected direct current.

2. The NERC whitepaper makes the claim near the top of page 4 "The 75 A per phase screening threshold was determined using single-phase transformers, but is applicable to all types of transformer construction." This claim is absurd on its face, even to nontechnical laypeople—it is like an automobile manufacturer conducting crash tests on three models of sedans and then claiming the results can be used to exempt all makes and models from further crash testing.

3. The NERC whitepaper makes the disclosure on the top of page 5 "The screening thermal model is based on laboratory measurements carried out on 500/16.5 kV 400 MVA single-phase Static Var Compensator (SVC) coupling transformer." A "coupling transformer" is used to support reactive power rather than transmit real power and therefore its test results are not applicable, except as a hypothetical construct.

4. On the top of page 5, the NERC whitepaper discloses that "Temperature measurements were carried out at relatively small values of GIC (see Figure 2)." In fact, when the whitepaper references with the more detailed test procedures were checked, we found that the test in Reference 2 was conducted under "no-load conditions" at 5 amps for 2 hours, followed by a maximum of 16.7 amps for only one minute. This unrealistic test

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was conducted far below the 75 amp Screening Criterion the standard proposes.[47]

Reference 2 for the NERC Screening Criterion whitepaper helpfully discloses the reason

more rigorous transformer tests under injected direct current conditions are not

performed—"***for fear of damaging the transformer***" (emphasis added). [48]

5. On the top of page 4, the NERC Screening Criterion whitepaper discloses that "Winding

hot spots are not the limiting factor in terms of hot spots due to half-cycle saturation,

therefore the screening criterion is focused on metallic part hot spots only." In fact,

winding hot spots have been the failure mode in several major incidents of transformer

GIC damage, the most notable example being the Salem 1 nuclear plant Phase "A" and

Phase "C" transformers during the March 1989 solar storm.

6. The NERC Screening Criterion whitepaper does not disclose that second transformer

test was conducted essentially under 20% or less load conditions, but this is disclosed in

Reference 3.[49]

7. Reference 4 of the NERC Screening Criterion whitepaper is apparently a workshop

presentation and is therefore unpublished.[50]

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[47] Reference 2 for the NERC Screening Criterion whitepaper is "Marti, L., Rezaei-Zare, A., Narang, A., "Simulation of Transformer Hotspot Heating due to Geomagnetically Induced Currents," IEEE Transactions on Power Delivery, vol.28, no.1, pp.320-327, Jan. 2013. On page 322 the test procedures are described:
 "As another illustration, Fig. 5 shows the measured response obtained during acceptance tests on a single-phase 500/16.5-kV, 400-MVA transformer, which we will call "Transformer B." These measurements were made under no-load conditions at Fig. 4. Asymptotic values of flitch plate hotspot temperature rise versus GIC (Transformer A).Fig. 5. Measured temperature rise in Transformer B (500/16.5 kV, 400 MVA) during dc injection tests. 26 C ambient using sensors placed at several parts of the assembly, including points in the tie plate and at suspected winding hotspots. A dc current of 5 A was injected into the winding for 2 h, followed by a further step increase to 16.7 A for 1 min. The fitted function for the tie-plate hotspot is shown in Fig. 6 for a 5-A step change in current. Since measurement of the response at the 16.7-A level was terminated after just 1min, as required by the specified acceptance tests, no further fitted parameters are available for this unit. In the absence of additional asymptotic temperature information, a simplified straight-line asymptotic behavior with a slope of 15.6/5.0 C/A, has been used for the purpose of illustrating results predicted with our formulation. Unfortunately, there are no winding hotspot measurements available for this unit."
[48] Reference 2 for the NERC Screening Criterion whitepaper helpfully discloses the reason more rigorous transformer tests under injected direct current conditions are not performed (emphasis added): Reference 2, page 325 reads:
"A more difficult issue is that most transformer manufacturers do not routinely perform dc current injection tests; some manufacturers are unable to perform the tests, and asset owners would be reluctant to carry out such tests for the current values needed to fully characterize the asymptotic temperature behavior such as the one shown in Fig. 4 *for fear of damaging the transformer*."
[49] See Lahtinen, Matti. Jarmo Elovaara. "GIC occurrences and GIC test for 400 kV system transformer". IEEE Transactions on Power Delivery, Vol. 17, No. 2. April 2002. Page 560 discloses:
"During the test, the winding temperature did not rise because the phase currents were rather low and were less than 20% of the rated ones."

Given the egregious defect of the 75 amp per phase Screening Criterion for transformer thermal impact assessments, it is helpful for the Commissioners to understand its history. Originally, the Standard Drafting Team set the Screening Criterion at 15 Amps, where it persisted at this level through Draft 1, Draft 2, Draft 3, and Draft 4 used as the basis for three separate ballots. When the standard failed on Ballot 3, the 15 amp Screening Criterion was upwardly reset by a *factor of five* to 75 amps, whereupon the standard handily passed on the next ballot.

The requirements of FERC Order 779 allowed for uniform assessment measures, not uniform measures to exempt transformers from assessment. The Commissioners should remand the 75 amp Screening Criterion for transformer thermal impact assessment.

Transformer Thermal Impact Assessments

With the average age of the extra high voltage transformers in the fleet up to 40 years old, it is not practical or reliable for utilities to perform transformer thermal impact assessments in most cases. Through the GMD Task Force, we have heard that some transformer manufacturers are providing "GIC withstand" warranties for new transformers. The Commission should remand the standard to require "GIC withstand" as a potential mitigation measure only for newly purchased transformers where the transformer manufacturer will warranty the transformer for a specified level of GIC withstand. The allowed GIC withstand amperage in a utility's transformer thermal impact assessment should never exceed the manufacturer's warranty; if the manufacturer will not provide a GIC withstand warranty, no hardware mitigation exception for transformer thermal impact assessment should be permitted under the standard.

Inadequate Protection of BPS Equipment and System Stability

In the GMD NOPR, FERC sought comment from NERC on conditions that could cause load loss due to system instability:

> 56. NERC maintains that Table 1 sets forth requirements for system steady state performance. NERC explains that Requirement R4 and Table 1 "address assessments of

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[50] Reference 4 is: "J. Raith, S. Ausserhofer: "GIC Strength verification of Power Transformers in a High Voltage Laboratory", GIC Workshop, Cape Town, April 2014."

the effects of GICs on other Bulk-Power System equipment, system operations, and system stability, including the loss of devices due to GIC impacts."

Table 1 provides, in relevant part, that load loss and/or curtailment are permissible elements of the steady state:

Load loss as a result of manual or automatic Load shedding (e.g. UVLS) and/or curtailment of Firm Transmission Service may be used to meet BES performance requirements during studied GMD conditions. The likelihood and magnitude of Load loss or curtailment of Firm Transmission Service should be minimized.

Discussion

57. The Commission seeks comment from NERC regarding the provision in Table 1 that "Load loss or curtailment of Firm Transmission Service should be minimized."

FERC was right to solicit comments from NERC, because defects in the standard could cause voltage collapse, High Voltage Direct Current (HVDC) link tripping, protective device tripping, and harmonic production.

Voltage Collapse and Reactive Power Modeling

In FERC Order 779 (p. 11), the Commission recognized that voltage instability and subsequent voltage collapse is one of several GMD scenarios:

16. We issue this directive recognizing, as we did in the NOPR, that there is an ongoing debate as to the likely effect of GMDs on the reliable operation of the Bulk Power System. As discussed below, the NOPR comments reflect these differing views, with some comments supporting the *NERC Interim GMD Report's conclusion that the worst-case GMD scenario is "voltage instability and subsequent voltage collapse,"* while other comments endorse the Oak Ridge Study's conclusion that a severe GMD event could put Bulk-Power System transformers at risk for failure or permanent damage.

Ironically, the standard does not require modeling of reactive power consumption and potential voltage collapse. Nonetheless, some network operators have begun to model for this scenario. For example, Bonneville Power Administration (BPA) modeled their network using PowerWorld™ and we were able to obtain the results through a Freedom of Information Act request.[51]

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[51] See BPA GMD Impact Assessment, TIP 264 GIC R&D," by Scott Dahman of PowerWorld Corporation for Bonneville Power Administration, September 30, 2013, filed as Resilient Societies' reference document 15 on FERC Docket No. RM15-11-000.

The BPA network model shows that voltage collapse occurs at a geoelectric field of 3.85 V/km:
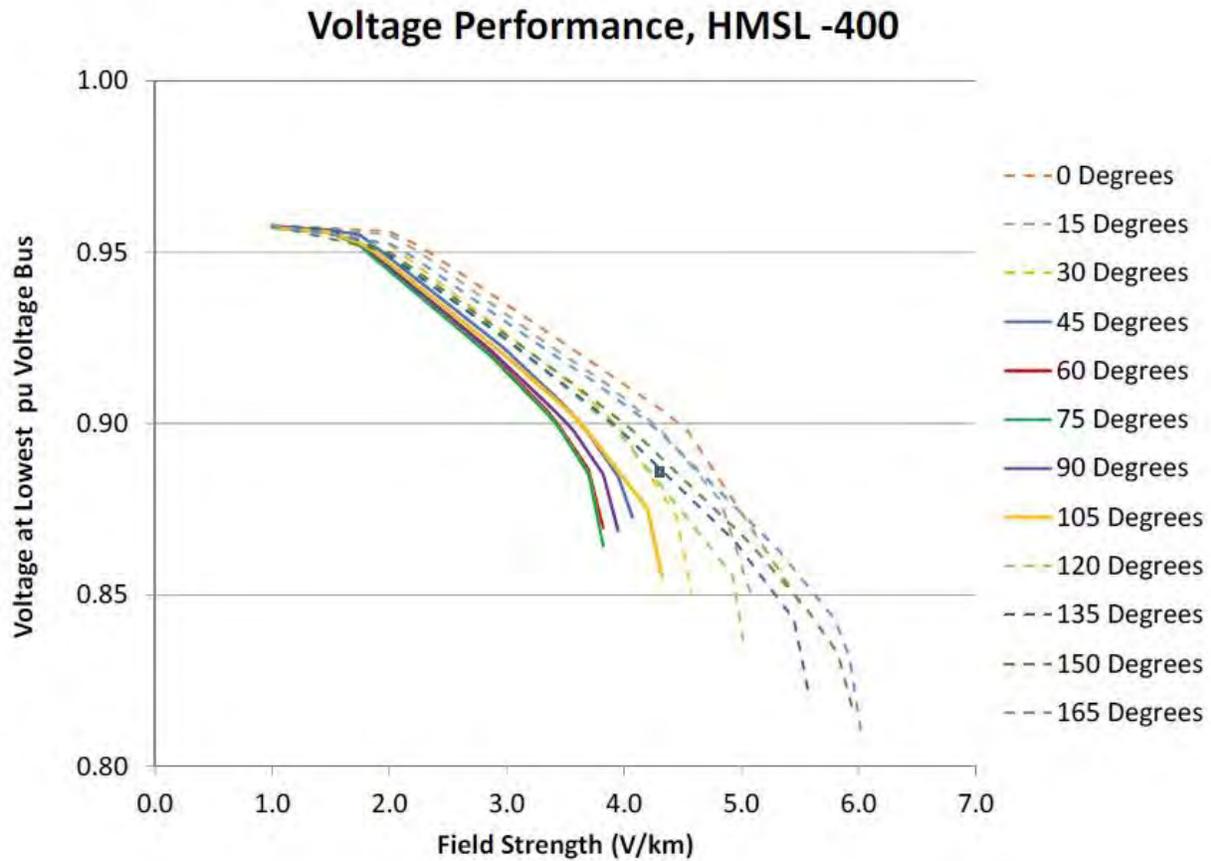
Figure 6

Figure 9: Voltage performance as a function of field strength and latitude

The BPA network is predominantly in the "PB-1 - Pacific Border (Willamette Valley)" physiographic region, with a scaling factor of 0.62 according to the NERC standard. The geomagnetic latitude of Portland, Oregon within the BPA network is 50.98 degrees, with a scaling factor of 0.35. The combined scaling factor is 0.22, resulting in a Benchmark GMD Event of 8 V/km in Quebec scaled down to 1.74 V/km at Portland. According to the BPA model, system voltage would be at approximately 95% at this field strength, within system stability limits.

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However, this example also shows the importance of a technically justified Benchmark GMD Event, combined with required modeling for voltage collapse. If the Benchmark GMD Event were set at 20 V/km in Quebec, the scaled geoelectric field at Portland would be 4.36 V/km; voltage collapse would occur under the Benchmark GMD Event.

(a) 1 V/km

(b) 2 V/km

(c) 3 V/km

(d) 3.85 V/km - last valid solution
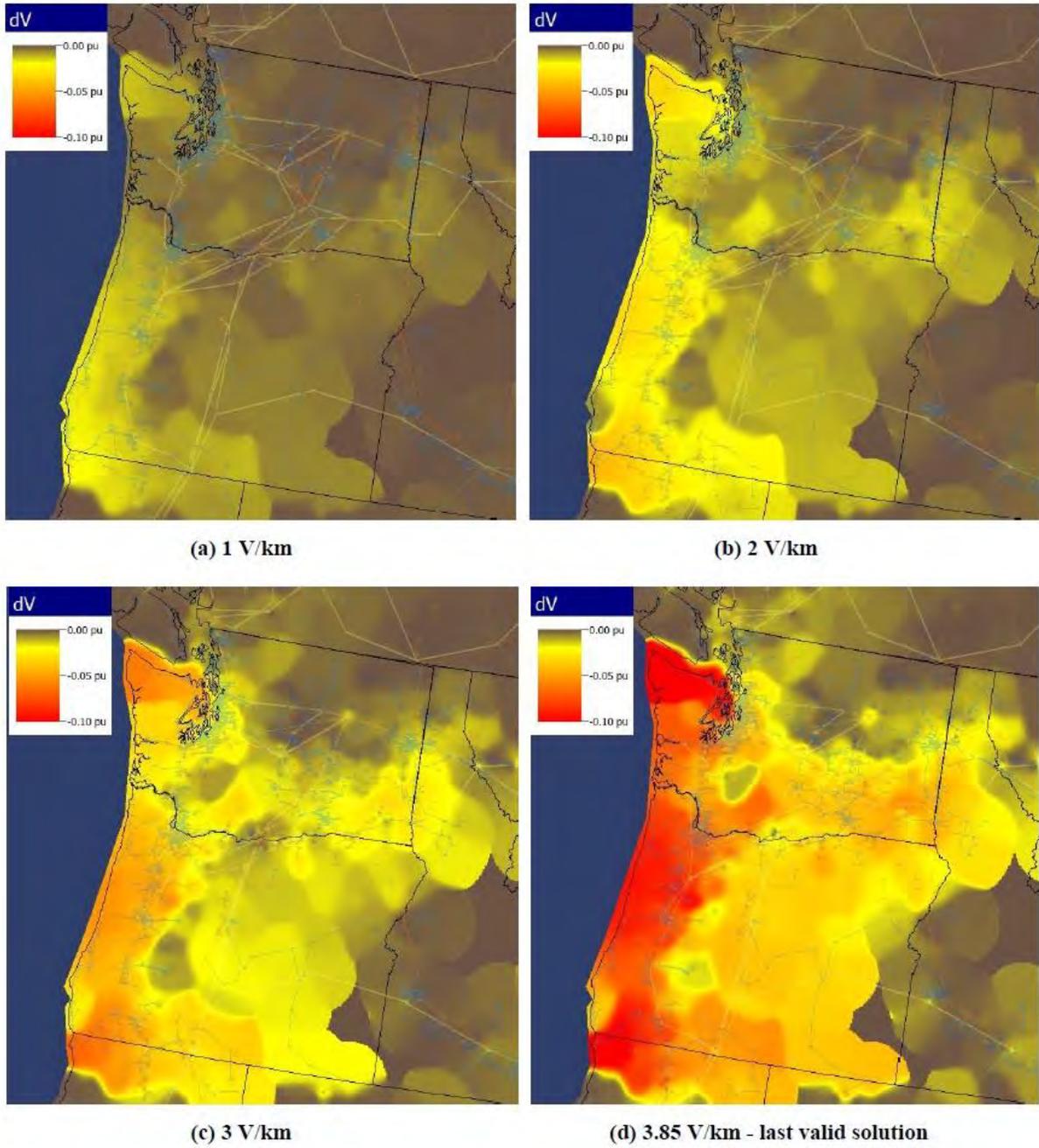
Figure 8 - Voltage Change Contours, HMSL -400, 75 degrees Electric Field Orientation

Figure 10: Voltage Change Contours

HVDC Tripping

Increasingly, High Voltage Direct Current (HVDC) links are transferring both power and potential outage contingencies over long distances and across the boundaries of Reliability Coordinators. Below is a table of HVDC links of capacity 250 MW and above within the United States, both operational and planned:

Major High Voltage Direct Current Ties
250MW and Above within United States

HVDC Link	End 1	Reliability Coordinator End 1	End 2	Reliability Coordinator End 2	Total Length (km)	DC Voltage (kV)	Power (MW)	First Year of Service
Tres Amigas Superstation	Clovis, New Mexico	SPP/ERCOT/Peak	Clovis, New Mexico	SPP/ERCOT/Peak	B-to-B	765	5,000*	2016
Pacific DC Intertie	Celilo, OR	Peak Reliability	Sylmar, CA	Peak Reliability	1,362	500	3,800	1970
Plains & Eastern Clean Line	Texas County, OK	SPP	Shelby County, TN	TVA	1,207	600	3,500	2018
Rock Island Clean Line	O'Brien County, IA	MISO	Grundy County, IL	PJM	805	600	3,500	2017
TransWest Express	Rawlins, WY	Peak Reliability	Las Vegas, NV	Peak Reliability	1,167	600	3,000	2015
Intermountain Power Project	Intermountain, UT	Peak Reliability	Adelanto, CA	Peak Reliability	785	500	2,400	1986
Phase II	Radisson, QC	Hydro Quebec, TE	Ayer, MA	ISO New England	1,480	450	2,000	1991
CU (Great River Energy HVDC)	Underwood, ND	MISO	Rockford, MN	MISO	687	400	1,000	1979
Neptune Cable (Long Island)	Hicksville NY	NY ISO	Sayreville, NJ	PJM	105	500	660	2007
Hudson Tranmission Project	Bergen County, NJ	PJM	New York City	NY ISO	10	180	660	2013
Welch HVDC	Titus County, TX	ERCOT	Mount Pleasant, TX	SPP	10	170	600	1995
Square Butte	Center, ND (Young)	MISO	Adolph, MN	MISO	749	250	500	1977
Trans Bay Cable	Pittsburg, CA	Peak Reliability	San Francisco, CA	Peak Reliability	85	200	400	2010
Cross Sound Cable	New Haven, CT	ISO New England	Shoreham, NY	NY ISO	40	150	330	2002

*Tres Amigas is planned for eventual 30 GW capacity.

Sources: IEEE, ABB, Siemens, Tres Amigas LLC, Wikipedia

Table 5: HVDC Ties

The trend of high capacity, long distance HVDC links is accelerating as more renewable generation is transported long distances for compliance with environmental regulations.

Real-world experience has shown that HVDC links are highly vulnerable to GMD events, because harmonics affect the firing angle of commutators.[52] As the above table shows, HVDC links present large contingencies up to 5,000 MW. It is a fallacy to assume that failures of bi-pole HVDC links will occur independently at different times, allowing contingency planning for

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[52] N. Mohan, V. D. Albertson, T. J. Speak, J. G. Kappenman, M. P.   Bahrman, "Effects of Geomagnetically-Induced Currents on HVDC Converter Operations," N. Bahrman, IEEE PAS Transactions, Vol. PAS-101, November 1982, pp. 4413-4418.

only half of the capacity. Experience with the Phase II link running from Radisson, Quebec to Sandy Pond, Massachusetts shows that both poles can fail during the same solar storm.

The Phase II link tripped during solar storms on 03/24/91, 05/28/91, 10/27/91, and 10/28/91. According to our calculations using the Standard TPL-007-1 geomagnetic scaling factors and ground model scaling factors, all of these trips occurred during solar storms at 21% or less of the NERC Benchmark GMD Event.

The FERC Commissioners should remand Standard TPL-007-1 for lack of a mandatory requirement for protection of HVDC links against GMD.

Disruptive Harmonic Production

FERC Order 779 (p. 5) recognized disruptive harmonics that can cause sudden collapse of the Bulk Power System.

> GICs can cause "half-cycle saturation" of high-voltage Bulk-Power System transformers, which can lead to increased consumption of reactive power and creation of disruptive harmonics that can cause the sudden collapse of the Bulk-Power System.

NERC's own report GMD Interim Report in 2012 described the impacts of harmonic production, including tripping of protective devices.[53]

FERC has a legislative mandate in Section 215 of the Federal Power Act to prevent system instability, including sudden collapse. The Commission should remand Standard TPL-007-1 because it does not contain any requirement for mitigation of harmonics that can cause system instability and unanticipated failure of system elements, including HVDC links, as we have shown in this comment.

Exemptions of Networks Operating Below 200 kV

The GMD NOPR (p. 10) recited the exemption of networks with high-side voltages below 200 kV:

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[53] 2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System," NERC, February 2012, available at http://www.nerc.com/files/2012GMD.pdf, last accessed on July 26, 2015.

13. NERC states that proposed Reliability Standard TPL-007-1 applies to planning coordinators, transmission planners, transmission owners and generation owners who own or whose planning coordinator area or transmission planning area includes a power transformer with a high side, wye-grounded winding connected at 200 kV or higher. NERC explains that the applicability criteria for qualifying transformers in the proposed Reliability Standard is the same as that for the First Stage GMD Reliability Standard in EOP-010-1, which the Commission approved in Order No. 797.

While the FERC-approved Bulk Electric System definition includes transmission at voltages at 100kV and above, and while multiple GMD impacts on Static VAR Compensators and other equipment operating between 100kV and 200kV were reported by electric utilities during the March 1989 solar storm, Standard TPL-007-1 would exempt Transmission Operators with equipment operating between 100 kV and 200 kV. Many Transmission Operators operate Static VAR Compensators, capacitors, and other equipment between 100 kV and 200 kV: equipment designed to provide reactive power and to stabilize transmission networks during GMD. Below is a listing of March 13, 1989 storm impacts on critical equipment operating at less than 200 kV, as disclosed by a FERC-sponsored study:

March 13, 1989 Geomagnetic Disturbance

Chronology of Reported North American Power Grid Events
Adapted from Pages A2-2 to A2-8 of "Geomagnetic Storms and Their Impacts on the U.S. Power Grid"
Oak Ridge National Laboratory, January 2010

Event No.	Date	Time (EST) From	To	Area or System	Event	Base kV	Comments
29	3/13/1989	245		Minn. Power	Capacitor	115	Lost capacitor bank at Nashwauk. Neut overcurrent relay
44	3/13/1989	608		Cent. Hud.	Capacitor	69	Pulvers Corners capacitor trip
47	3/13/1989	615		APS	Capacitor	138	7 Capacitors tripped
54	3/13/1989	618		Va. Pwr.	Capacitor	115	Virginia Beach
57	3/13/1989	619		Cent. Hud.	Capacitor	115	Hurley Ave. capacitor trip
94	3/13/1989	1645	2000	WPL	Voltage	138	Various voltage problems. Regulators hunting
100	3/13/1989	1655		Atl. Elec.	Voltage	69	
108	3/13/1989	1658		BPA	Capacitor	115	Tripped by neutral time ground at 4 substations
175	3/13/1989	2017		NEPOOL	Capacitor	115	Orrington capacitors (1, 2, &3) opened and would not close
183	3/13/1989	2020	2030	Atl. Elec.	Voltage	138	
192	3/13/1989	2032		PJM		69	Nazareth Capacitors tripped

Table 6: Impacts on equipment operating below 200kV during 1989 GMD event

These are real-world and non-trivial GMD impacts during a moderate storm with geoelectric fields of only 2 volts/kilometers in high latitude Quebec.

We researched reactive power support equipment installed in the United States and found three sources: lists of reference accounts published by ABB and Siemens, and individual company disclosures. Notably, there was a high degree of overlap between the three sources. It appears ABB produces the vast majority of SVC/STATCOM for the United States. Based on the ABB sample, we estimate that about 25% of SVC/STATCOM units within the bulk electric system of the United States operate between 100 kV and 200 kV. Reactive power is in particularly short supply during GMD events because transformers in half-cycle saturation consume reactive power. Unexpected tripping of reactive power resources can cause both system separation and cascading system collapse. In fact, the proximate cause of the March 1989 Hydro Quebec

blackout, occurring in only 93 seconds, was loss of seven SVC's, all tripping within a 59 second interval.[54]

Below is an example list of reactive power resources within the United States operating between 100 kV and 200 kV, the vast majority installed since 1989:

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[54] See S. Renaud and S. Guillon, "Hydro-Québec and GIC: Power Network Studies and Simulation Developments," Presentation of HQ to the JRC Workshop, Ispra, Italy, Oct. 29, 2013, at VG 6, 16, 18 and 24 of 56. See http://ipsc.jrc.ec.europa.eu/fileadmin/repository/sta/SpaceWeatherWorkshop/Session-3_Guillon.pdf.

Examples of Reactive Power Resources 100-200 kV
within United States

Equipment	Utility	Location	Voltage (kV)	First Year of Service	Inductive Rating (MW)	Capacitive Rating (MW)
SVC	AEP	Beaver Creek	138	1978	0	0
SVC	Kansas Gas & Electric	Murray Gill, KS	138	1985	25	200
SVC	Kansas Gas & Electric	Gordon Evans, KS	138	1985	0	300
SVC	Alaska Energy Authority	Soldatna, AK	115	1991	40	70
SVC	Alaska Energy Authority	Daves Creek, AK	115	1991	10	25
SVC	Virginia Power	Colington, VA	115	1996	30	167
STATCOM	COM Central and South West Corp	Eagle Pass HVDC	138	1999	72	72
SVC	Connectiv	Nelson	138	1999	100	150
SVC	ISO Ispat	Ispat	138	1999	0	200
STATCOM	Austin Energy	Holly, USA	138	2003	80	110
SVC	Pacific Gas & Electric	Potero, CA	115	2003	100	240
SVC	Golden Valley Electric Association	Jarvis Creek	138	2004	8	45
SVC	Georgia Power Co	Noth Dublin, GA	115	2005	unknown	unknown
SVC	Duke Power	Beckerdite	100	2006	100	300
SVC	Tucson Electric Power	Tucson, AZ	138	2006	75	200
SVC	Dominion Power	Colington, VA	115	2007	0	0
SVC	Nstar	Barnstable, MA	115	2008	113	225
SVC	Oncor	Renner 1	138	2008	265	300
SVC	Oncor	Parkdale 1	138	2008	265	300
SVC	Oncor	Parkdale 2	138	2008	265	300
SVC	Oncor	Renner 2	138	2009	265	300
SVC	AEP	Hamilton 1	138	2011	25	100
SVC	AEP	Hamilton 2	138	2011	25	100
SVC	Pepco (PHI)	Nelson	135	2011	0	0
SVC	Rochester Gas & Electric	Station 124, NY	115	2011	100	200
SVC	Pepco (PHI)	Ocean City, MD	138	2012	75	75
SVC	Entergy	Porter, TX	138	unknown	unknown	unknown
STATCOM	San Diego G&E	Talega, CA	138	unknown	unknown	unknown
STATCOM	Vermont Electric	Burlington, VT	115	unknown	unknown	unknown
Source: ABB, Siemens, Company Disclosures						

Table 7: List of Reactive Power Resources, 100-200 kV, in United States

In 2013 BPA commissioned a PowerWorld study of vulnerability of its network to GMD.[55] Interestingly, the study concluded that coastal 115 kV networks are especially susceptible to voltage drop.

> **Uniform Field Analysis Conclusions**
>
> The uniform field analysis reveals some vulnerability of the Pacific Northwest power grid due to GIC transformer reactive power losses. *The Olympic peninsula and coastal 115 kV networks are especially susceptible to voltage drop.* The HMSL +550 scenario performs slightly better than the HMSL -400 scenario, likely a result of it having more spinning generator reactive power reserves. GMD electric field orientations of 60-90 degrees pose the greatest threat in both scenarios. The next phase of analysis will examine methods to increase the ability of the network to withstand GMD events.

The arbitrary exemption of networks operating between 100 kV and 200 kV, without any specific study by owners and operators, is technically unreasonable, discriminatory, preferential, and inconsistent with real-world scientific evidence. Critical equipment can operate between these voltages, as the examples for SVCs, STATCOMs, and HVDC links show. Modeling within the BPA system shows that 115 kV networks are vulnerable to GMD. The Commission should remand to eliminate the exemption for networks operating between 100 kV and 200 kV.

Safety Factors and Multiplicative Impacts of Defective Assumptions

FERC Order 779 (p. 43) recited the position of the Electric Infrastructure Security (EIS) Council on safety factors:

> "EIS states that, because the science of GMDs is inexact, an event twice as large as the largest expected GMD should be used as a safety margin."

 The Commission was right to recite this comment, because safety factors are commonly used in a variety of engineered structures and products. For example, a safety factor of 2 is commonly used in built structures. Automobiles commonly have a safety factor of 3.[56]

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[55] See "BPA GMD Impact Assessment, TIP 264 GIC R&D," by Scott Dahman of PowerWorld Corporation for Bonneville Power Administration, September 30, 2013, filed as Resilient Societies' reference document 15 on FERC Docket No. RM15-11-000.

[56] See "Factor of Safety," Wikipedia, available at https://en.wikipedia.org/wiki/Factor_of_safety, last accessed 7/25/2015.

However, the "Implicit Safety Margin" in Standard TPL-007-1 is only 1.4 (8 V/km over 5.77 V/km.)

The Commission should recognize that several of the potential defects in Standard TPL-007-1 have multiplicative impact—in other words, biases in the NERC Benchmark GMD Event and transformer thermal Screening Criterion multiply among themselves, producing a level of required protection that may be many times below a prudent and technically justified level.

In the below table, we show a "NERC Scenario" consistent with Standard TPL-007-1 and other reasonable scenarios designated "Middle" and "Conservative," along with the multiplicative impact of alternative assumptions. Notably, key elements of the other reasonable scenarios are based on preliminary results by scientists on the NERC GMD Task Force or, alternatively, were part of draft versions of Standard TPL-007-1. For example, the GMD Task Force proposed 1-in-100 Year Reference Storm peak geoelectric fields of 20 V/km and 40 V/km in July and February 2013, respectively. As another example, a threshold of 15 amps for the transformer thermal Screening Criterion was embedded in Standard TPL-007-1 for Drafts, 1, 2, 3, and 4.

Multiplicative Impacts of Geomagnetic Disturbance Scenario Assumptions
NERC Standard vs. Other Reasonable Scenarios at Specific Locations

Values from References	Scenario		
	NERC Standard	Middle	Conservative
Benchmark GMD Event			
1-in-100 Year Reference Storm	5.77 V/km	20 V/km	40 V/km
NERC "Implicit Safety Margin"	1.4	n/a	n/a
1-in-100 Year Reference Storm with "Safety Margin"	8 V/km	20 V/km	40 V/km
Geomagnetic Latitude Scaling Factor within U.S.	0.1 to 0.5	0.30	0.50
Ground Model Scaling Factor within U.S.	0.22 to 1.17	0.70	1.17
Transformer Assessment			
Thermal Impact Screening Criterion	75 Amps	45 Amps	15 Amps
Multiplicative Impact Ratios	Scenario		
(Ratios: Middle & Conservative to NERC Standard)	NERC Standard	Middle	Conservative
Benchmark GMD Event			
1-in-100 Year Reference Storm (V/km)	1.0	2.5	5.0
Geomagnetic Latitude Scaling within U.S.	1.0	3.0	5.0
Ground Model Scaling Factor within U.S.	1.0	3.2	5.3
Multiplicative Product for Benchmark GMD Event	1.0	23.9	133.0
Transformer Thermal Assessment			
Thermal Impact Screening Criterion (amps)	1.0	3.0	5.0
Overall Safety Factor	1.0	2.0	3.0
Total Multiplicative Products for All Assumptions	1	143	2,000

Notes:

1. "Middle" and "Conservative" 1-in-100 Year Reference Storm scenarios from work of NERC GMD Task Force.

2. "Middle" Geomagnetic Scaling Factor is midpoint of NERC Standard's range within U.S. latitudes.

3. "Conservative" Geomagnetic Scaling Factor is high-point of NERC Standard's range within U.S. latitudes.

4. "Middle" Ground Model Scaling Factor is midpoint of NERC Standard's range within U.S. latitudes.

5. "Conservative" Ground Model Scaling Factor is high-point of NERC Standard's range within U.S. latitudes.

6. "Middle" Thermal Impact Screening Criterion is midpoint of 75 and 15 amps.

7. "Conservative" Thermal Impact Screening Criterion at 15 amps is NERC Standard value for Ballots 1 and 2.

8. "Middle" Safety Factor is standard value for built structures.

9. "Conservative" Safety Factor is standard value for automobiles.

Table 8: Multiplicative Impacts of GMD Scenario Assumptions

We urge the Commission to understand that fixing just one factor in Standard TPL-007-1, such as the 1-in-100 Year Reference Storm, will not fix all the other defective standards. Importantly, because the various component factors are multiplicative, the overall impact of hazard-reducing sub-models is to drastically reduce the prudence and the realism of the resulting Benchmark GMD Event design and benchmark standard.

We further urge the Commission to add a requirement that utilities annually disclose the number of extra high voltage transformers in their fleet, the number undergoing thermal assessment, the number of transformers determined to need mitigative measures, and the number and categories of mitigative measures among hardware protection, spare units, isolation from service, or other mitigative strategy. If the disclosed number of transformers needing thermal assessment and/or the number of transformers with installed hardware protection or other mitigative measures is trivial, then the Commission will know that the intent of FERC Order 779 for hardware protection is being evaded.

Responses to FERC Solicitation of Comments

GIC Monitoring Devices

GMD NOPR, p. 28:

> 46. The Commission proposes to direct NERC to develop revisions to Reliability
> Standard TPL-007-1 requiring installation of monitoring equipment (i.e., GIC monitors
> and magnetometers) to the extent there are any gaps in existing GIC monitoring and
> magnetometer networks, which will ensure a more complete set of data for planning and
> operational needs. Alternatively, we seek comment on whether NERC itself should be
> responsible for installation of any additional, necessary magnetometers while affected
> entities would be responsible for installation of additional, necessary GIC monitors. As
> part of NERC's work plan, we propose to direct that NERC identify the number and
> location of current GIC monitors and magnetometers in the United States to assess
> whether there are any gaps.

GMD NOPR, p. 29:

> 47. NERC maintains that the installation of monitoring devices could be part of a
> mitigation strategy. We agree with NERC regarding the importance of GIC and
> magnetometer data. As the Commission stated in Order No. 779, the tools for assessing
> GMD vulnerabilities are not fully mature. Data from monitors are needed to validate the

analyses underlying NERC's proposed Reliability Standard and the analyses to be performed by affected entities.

NOPR, p. 30:

48. Accordingly, rather than wait to install necessary monitoring devices as part of a corrective action plan, GIC and magnetometer data should be collected by applicable entities at the outset to validate and improve system models and GIC system models, as well as improve situational awareness. To be clear, we are not proposing that every transformer would need its own GIC monitor or that every entity would need its own magnetometer. Instead, we are proposing the installation and collection of data from GIC monitors and magnetometers in enough locations to provide adequate analytical validation and situational awareness. We propose that NERC's work plan use this criterion in assessing the need and locations for GIC monitors and magnetometers.

Geomagnetically-Induced Current (GIC) monitors are commercially available and can be purchased for as little as $10,000 to $15,000 each.[57] Nonetheless, Standard TPL-007-1 has no requirement for GIC monitoring or mandatory sharing of GIC data for scientific study. We agree with the Commission that Standard TPL-007-1 should be remanded for mandatory installation of GIC monitors and magnetometers. Moreover, data from these GIC monitors and magnetometers should be made available to the public to better scientific understanding of GMD effects on the electric grid.

Public Dissemination of GIC Data

In the GMD NOPR (p. 24), the Commission sought comment on barriers to public dissemination of GIC and magnetometer readings:

The Commission seeks comment on the barriers, if any, to public dissemination of GIC and magnetometer readings, including if the dissemination of such data poses a security risk and if any such data should be treated as Critical Energy Infrastructure Information or otherwise restricted to authorized users.

Resilient Societies supports making GMD data (e.g., GIC monitoring and magnetometer data) available to researchers for study and for publication, peer review, and professional workshop

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[57] See Resilient Societies Findings and Recommendations to the Maine Public Utilities Commission in Maine PUC Docket 2013-00415, October 15, 2013 and December 18, 2013. Costs of commercially available GIC monitoring and automated remote readout have declined from $200,000 per unit to $10,000 to $15,000 per monitoring unit over the past two years. See http://resilientsocieties.org/docketfilings.html, last accessed March 23, 2014.

critique. The Commission should order applicable entities to establish regular procedures for public dissemination of GIC and magnetometer readings. Without disclosure and dissemination of GIC and magnetometer readings, FERC will be enabling an industry-controlled machinery—the NERC reliability-standard-setting process—to generate and perpetuate liability protections without strong technical basis. Concurrently, FERC will aid and abet the protection of electric utility investors while shifting economic losses and societal disruptions from prolonged blackout caused by GMD to all other groups in our society.

The risk of blackout from GMD has been well known since the Hydro Quebec outage in March 1989. However, GIC data has been held as confidential and proprietary by the EPRI SUNBURST consortium and also by individual utilities. This practice has greatly impeded independent scientific study of GMD effects and caused inadequate technical understanding. Non-disclosure of GIC data and GMD impacts further impeded the setting of a technically justified Benchmark GMD Event, a Screening Criterion for transformer thermal assessment, and other necessary requirements and measures in the standard.

There is no security risk to releasing GIC and magnetometer readings. These are indicators of naturally occurring phenomena and their non-disclosure will have absolutely no preventative effect on whether GMD disasters occur or not. Already, GIC data is made available in real time by BPA on their website. TVA has released GIC data under the Freedom of Information Act. On a selected basis, individual private utilities have also released GIC data at the GMD Task Force and other venues. Utilities have disclosed the locations of over 100 GIC monitoring sites.

In order for GIC data to be relevant and actionable for scientific study, it must necessarily include the location of the monitor. Some monitors are located at critical substations and some are located at non-critical substations. As the number of monitors increases and ultimately will number several hundred, the colocation of a GIC monitor will be a very poor indicator of whether a substation is critical or not. Already, there are over 100 GIC monitors installed. Moreover, the location of electric grid substations is not protected information—substation locations are freely available via commercially available databases, including the ubiquitous Google Earth online mapping service.

FERC Order No. 683 clarified the definition of Critical Energy Infrastructure Information (CEII) (pp. 4-5):

> CEII is clarified as specific engineering, vulnerability, or detailed design information about proposed or existing critical infrastructure that: (1) relates details about the production, generation, transportation, transmission, or distribution of energy; (2) could be useful to a person in planning an attack on critical infrastructure; (3) is exempt from mandatory disclosure under the Freedom of Information Act, 5 U.S.C. 552 (2000); and (4) does not simply give the general location of the critical infrastructure. The particular clarifications consist of adding the words "specific engineering, vulnerability, or detailed design" at the Docket No. RM06- 24-000 - 5 - beginning of § 388.113(c)(1) and adding the words "details about" at the beginning of § 388.113(c)(1)(i).

> 7. The Commission further clarifies that narratives such as the descriptions of facilities and processes are generally not CEII unless they describe specific engineering and design details of critical infrastructure.

In order for GIC and magnetometer readings to be considered CEII, they must meet all four conditions specified in FERC Order 683. These readings fail on all four conditions:

1. GIC and atmospheric magnetic fields are not usable "energy."

2. GIC and magnetometer readings would not be useful to persons planning a terrorist attack, because that person could not use real-time or delayed readings to predict GMD events in the future. In fact, public forecasts by the NOAA Space Weather Prediction Center would have more utility for terrorists, but because these forecasts are not restricted as CEII, neither should real-time readings be restricted for security reasons.

3. By releasing GIC readings under the Freedom of Information Act multiple times, the U.S. Government has established that this information is not exempt from mandatory disclosure.

4. Any locational data with GIC and magnetometer readings could simply give the location of the monitor, i.e., latitude and longitude, and need not give any other information about critical infrastructure. FERC Order 683 specifically states that general location is not CEII.

Lastly, it would be unprecedented for a federal agency to restrict public use of information on naturally occurring hazards. There would be public outrage if readings on earthquakes, floods,

hurricanes, and the like were restricted and there will be similar outrage if information on solar storm hazards is concealed from the public. Restriction of public dissemination of GIC and magnetometer readings may be in the interest of electric utilities seeking to avoid the installation of hardware protective devices, but it is not in the public interest.

Lowest Common Denominator Standard

FERC Order 672[58] established that a mandatory Reliability Standard should not reflect "the lowest common denominator," and should have no undue effect on competition. Moreover, the Commission established that it will not defer to the ERO with respect to a Reliability Standard's effect on competition. The Commission rejected the notion that an ANSI-certified process automatically satisfies the statutory standard of review for discriminatory impact or negative effect on competition. The relevant paragraphs from Order 672 are quoted below:

> 29. A mandatory Reliability Standard should not reflect the "lowest common denominator" in order to achieve a consensus among participants in the ERO's Reliability Standard development process. Thus, the Commission will carefully review each Reliability Standard submitted and, where appropriate, *remand an inadequate Reliability Standard to ensure that it protects reliability, has no undue adverse effect on competition*, and can be enforced in a clear and even-handed manner. Further, the Final Rule allows the Commission to set a deadline for the ERO to submit a proposed Reliability Standard to the Commission to ensure that the ERO will revise in a timely manner a proposed Reliability Standard that is not acceptable to the Commission. These provisions, as well, will strengthen the ERO and Regional Entities by providing mechanisms to achieve effective and fair Reliability Standards.

> 40. The Commission may approve a proposed Reliability Standard (or modification to a Reliability Standard) if it determines that it is just, reasonable, not unduly discriminatory or preferential, and in the public interest. In its review, the Commission will give due weight to the technical expertise of the ERO or a Regional Entity organized on an Interconnection-wide basis with respect to a proposed Reliability Standard to be applicable within that Interconnection. *However, the Commission will not defer to the ERO or a Regional Entity with respect to a Reliability Standard's effect on competition.*

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[58] FERC Statutes and Regulations, Rules Concerning Certification of the Electric Reliability Organization; and Procedures for the Establishment, Approval, and Enforcement of Electric Reliability Standards, Order No. 672, February 17, 2006, Docket No. RM05-30-000.

332. *As directed by Section 215 of the FPA, the Commission itself will give special attention to the effect of a proposed Reliability Standard on competition.* The ERO should attempt to develop a proposed Reliability Standard that has no undue negative effect on competition. Among other possible considerations, a proposed Reliability Standard should not unreasonably restrict available transmission capability on the Bulk-Power System.

338. We reject the notion that we should presume that a proposed Reliability Standard developed through an ANSI-certified process automatically satisfies the statutory standard of review. In this regard, *we agree with EEI and others that the development of a Reliability Standard through the ERO's stakeholder process is no guarantee that a proposed Reliability Standard does not have a discriminatory impact or negative effect on competition* even if the proposal meets its technical or operational objective beyond any restriction necessary for reliability and should not limit use of the Bulk-Power System in an unduly preferential manner. It should not create an undue advantage for one competitor over another.

(Italics added.)

Standard TPL-007-1 is a "lowest common denominator" that allows a protection level below the true threat or "technically justified" Benchmark GMD Event. Competitors that contemplate "best practices" above the deficient Benchmark GMD Event may not achieve cost-recovery and will be competitively disadvantaged, therefore establishing an undue effect on competition. The reality is that the "floor" of minimal reliability standards when combined with the promise of liability protection drives out "best practices" in the marketplace for reliability.[59]

The Commission Lacks Authority to Grant Liability Shielding

In FERC Order No. 779, para. 84, the Commission addressed the fears of some industry commentators that the FERC-regulated utilities might be subject to "strict liability" for "failure

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[59] On July 21, 2015 at the Electric Infrastructure Security Council Summit VI, FERC Commissioner LaFleur indicated that the minimal standards for "electric reliability" should not preclude both the adoption of "best practices" and eligibility for cost recovery for providing protections above the minimal level required by reliability standards.

  To the contrary, at the state level we have witnessed both Public Utility Commission staff in Maine and state legislators question why protective devices should be allowed if they exceed minimal NERC-FERC standards. Moreover, we have witnessed Central Maine Power identify appropriate protective equipment (such as 8 neutral blocking devices), then decline to budget for such equipment upon balloting of the proposed NERC-FERC standard. Further, NextEra Energy subsidiaries at both Point Beach, Wisconsin and Seabrook, New Hampshire have opted not to provide hardware protection for large transformers at high-vulnerability locations: for both the recently installed Point Beach GSU transformer and the soon-to-be installed Seabrook GSU transformer.

to ensure the reliable operation of the Bulk-Power System in the face of a GMD event of unforeseen severity...."

The Commission observes in FERC Order 779 (p. 55):

> 84. The Second Stage GMD Reliability Standards should not impose "strict liability" on responsible entities for failure to ensure the reliable operation of the Bulk-Power System in the face of a GMD event of unforeseen severity, as some commenters fear. The NOPR proposed to require owners and operators to develop and implement a plan so that instability, uncontrolled separation, or cascading failures of the Bulk-Power System, caused by damage to critical or vulnerable Bulk-Power System equipment, or otherwise, will not occur as a result of a GMD. While this language is taken directly from the definition of "reliable operation" in FPA section 215(a)(4), and similar language is found in the Requirements of other Reliability Standards, we clarify that owners and operators should be required to develop and implement a plan to protect against instability, uncontrolled separation, or cascading failures of the Bulk-Power System, caused by damage to critical or vulnerable Bulk-Power System equipment, or otherwise, as a result of a benchmark GMD event. The goal of the NERC standards development process should be to propose Reliability Standards that ensure the reliable operation of the Bulk-Power System in response to identified benchmark GMD events.

FERC Order 779, Para. 85 continues:

> "... Identifying robust and technically justified benchmark GMD events in the Reliability Standards, that the Bulk-Power System is required to withstand (i.e., continue "reliable operation"), addresses the concern that responsible entities might otherwise be required to prevent instability, uncontrolled separation, or cascading failures of the Bulk-Power System when confronted with GMD events of unforeseen severity. In addition, the Reliability Standards should include Requirements whose goal is to prevent instability, uncontrolled separation, or cascading failures of the Bulk-Power System when confronted with a benchmark GMD event. *Given that the scientific understanding of GMDs is still evolving, we recognize that Reliability Standards cannot be expected to protect against all GMD-induced outages.* (Emphasis added.)

Resilient Societies is troubled by FERC's delegation to NERC for selection of the Benchmark GMD Event, combined with the potential for liability relief if that solar storm intensity or duration is exceeded. Resilient Societies agrees that strict liability may not be imposed by courts of competent jurisdiction for unforeseen events. However, multiple blackouts due to GMD events have already occurred, both in North American and Europe, so utilities should be liable for failure to cost-effectively protect against severe GMD. We do not ask for strict liability,

but we ask the Commission to clarify its expectation that the FERC jurisdictional entities will be held to account, and be subject to liability in the event of gross negligence or willful misconduct in planning for and mitigating solar geomagnetic storms.

It is troubling that NERC has selected a Benchmark GMD Event that appears to be a roughly one in 20 year or 1 in 25 year moderate level solar storm rather than the 1-in-100 year solar storm that NERC claims to have modeled. Various filings by John Kappenman, a recognized expert in solar storm phenomena, assert that the intensity of the so-called 1 in 100 GMD event in the NERC benchmark model has been exceeded in intensity by several lower intensity GMD events in the past forty years.

The GMD Benchmark Event is apparently designed to exclude the most severe solar storms that would cause prolonged blackouts. What will the Commission do to hold electric utilities financially responsible for potential manipulation of the Benchmark GMD Event? We ask the Commission to recognize that the primary purpose of the Reliability Standard functions of the Commission, established in the aftermath of the U.S.-Canadian Blackout of 2003, was to enhance bulk power system reliability and reduce the likelihood and consequences of large-scale electric blackouts.

The traditional view of the authority of the Commission preceding the Energy Policy Act of 2005 was that the Commission lacked legal authority to grant immunity from liability by setting reliability standards. "Prior to unbundling, retail tariffs were primarily a matter for state regulation, and most states had approved tariff provisions permitting utilities to limit their liability for service interruptions to instances of gross negligence or willful misconduct."[60]

Hence FERC acted as if it "lacks authority to approve liability limitations in RTO [Regional Transmission Organization] tariffs."[61]

It is within the power of the U.S. Congress to set limits on liability by statute. We assert that it would be beyond the power of the Commission to grant a liability shield for the failure, by gross

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[60] Quoting Transmission Access Policy Study Group, 225 F.3d 667 at 727-728 (D.C. Cir. 2000).
[61] Ibid., at pp. 728-729.

negligence or willful misconduct, for electric utilities to invest in cost-effective measures to protect the bulk power system from geomagnetic storms that have geoelectric fields in excess of the NERC Benchmark GMD Event, or more extensive duration, or that involve the entirely foreseeable "cannibalizing" or overtaking of one solar storm by another.[62]

We ask the Commission to recognize that arbitrary liability limits above a GMD Benchmark Event, a Screening Criterion for transformer thermal impact, and other exemption avenues may be unsupported by independent scientific investigation. Unwarranted "escape hatches" in the standard that were not developed in conformity with the normal scientific methods cause economic externalities and market failures to invest in greater electric grid reliability.

To offer blanket liability limits does not align with market incentives to prevent harm if liability and accountability persist. In the realm of cybersecurity, there is an important distinction between liability shielding for voluntary reporting of cyber attacks and liability protection for underlying malfeasance in preventing cyber attacks.

As former U.S. Senator Jay Rockefeller observed in a letter on general liability protection for cyber security failures, liability protection "would turn existing market incentives for implementing best practices on their head."[63]

In the market for cyber protection and cyber insurance, the existence of cyber damage liability provides market opportunities for cyber insurance. Thus, the cyber insurance industry has incentives to assist insureds in adopting best practices, and in awarding insurance premium discounts to those entities that adopt best practices. [64]

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[62] FERC has refrained from extending liability protections in Orders No. 693 and No. 890. See also the consideration of liability exclusions, but their ultimate rejection following the "Policy Statement on Matters Related to Bulk Power System Reliability," 69 FR 22502 at 22507 (April 26, 2004).

[63] Letter from Senator Jay Rockefeller, June 3, 2013, cited by U.S. Department of Commerce.

[64] In a recent July 2015 report by Lloyds, the Business Blackout Report, provided as Reference Document No. 12 in Resilient Societies' filing in Docket RM15-11-000, the financial consequences of an extended power outage may exceed $1 trillion dollars for a 30 day blackout in the United States. A solar geomagnetic storm can have comparable economic damage and loss of life. See ongoing economic modeling by Jon D. Bate, a Resilient Societies' Intern in Appendix 1.

Some have proposed that the Commission limit the liability of Regional Transmission Organizations.[65] We strongly disagree. In particular, Resilient Societies finds it particularly troubling that the PJM Interconnection, Inc. (an RTO with sophisticated market mechanisms and planning capabilities) has, via its participation in the NERC Standard Drafting Team, promoted a Benchmark GMD Event and Screening Criterion for transformer thermal assessment that exempts consideration of hardware protection for transformers at nuclear power plants that have already failed during GMD events far smaller than the benchmark event. Of particular concern are nuclear power plants built upon the artificial island adjacent to coastal waters of Delaware Bay: Salem-1, Salem-2, and Hope Creek; and the nuclear power plants at Limerick (1 and 2) that experience saline boundary conditions during high tides, and that have apparently required down-rating of power generation during solar GMD events.[66]

If the NERC Benchmark GMD Event and Screening Criterion for transformer thermal assessment are suspect, or unscientific, or anti-scientific, at least the continuation of liability exposure can be a counterforce for prudence over the long run.

Were the Commission to assert that it has authority, without a future Act of Congress, to grant liability shielding for foreseeable harm from GMD events above the NERC GMD Benchmark Event, Resilient Societies would oppose such Commission action. We would claim that the Commission would be assuming *ultra* vires authority, and in the process placing the security of critical infrastructures at risk.

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[65] See e.g., Pierce, "Regional Transmission Organizations: Federal Limitations Needed for Tort Liability," 23 Energy L. J. 63-80 (2002).

[66] In a presentation at a GMD Workshop at Idaho National Laboratory on April 7-8, 2015, the Chairman of the Standard Drafting Team of NERC, Mr. Frank Koza, presented an ordered list of extra high voltage transformers that would require hardware protection assessment (2 EHV transformers in the AEP system above 75 amps per phase); and a ranked list of others that do not require assessment. Exempted from these dubious screening criteria for transformer thermal assessment are the transformers at the PSEG Salem nuclear plants
that have already failed during solar storms. The Koza presentation on April 8, 2015 is included in Resilient Societies' Reference Documents as Ref Doc. No. 4 in this Docket.

Economic Externalities in Solar Storm Protective Measures

A 2012 study by the North American Electric Reliability Corporation (NERC) hypothesized that the most likely severe GMD scenario would be system collapse due to voltage instability, with restoration times "a matter of hours to days," if replacement transformers were readily available or unnecessary in most cases.[67] An alternative report commissioned by Oak Ridge National Laboratory and sponsored by the U.S. Department of Energy, U.S. Department of Homeland Security, and Federal Energy Regulatory Commission concluded the most likely scenario is long-term outage due to extra high voltage transformer damage, with outage periods of months to years.

Since private utility companies do not bear the full risk-adjusted societal cost of an outage, but only their own risk-adjusted costs, utilities have lower economic incentive to protect against GMD events—absent subsidy in the form of cost recovery for protective devices, strict regulatory standards, and/or legal liability via negligence claims. In contrast, society as a whole has significant economic incentive to protect against even short-term blackouts of "hours or days."

Protecting the bulk power grid against a severe GMD event creates a positive externality that benefits our electricity-dependent society in the form of avoided power outage costs. Since private utilities do not currently have sufficient incentive to invest in the socially optimal level of grid protection, the gap in protection requires government action in the form of subsidy (cost recovery for protective equipment), regulation, and/or establishment of legal liability for negligence. For more details, including summary results of an economic model confirming these conclusions, please see the draft paper, "Preliminary Economic Analysis of Electric Grid Protection Against Geomagnetic Disturbance (GMD) Events" in Appendix 1 of this comment.

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[67] 2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System," NERC, February 2012, available at https://www.frcc.com/Public%20Awareness/Lists/Announcements/Attachments/105/GMD%20Interim%20Report.pdf, last accessed on July 27, 2015.

Unperformed "Initial Actions" Assessments

In FERC Order 779, the Commission ordered "Initial Actions" assessments to be performed by NERC, at NERC's own suggestion. These assessments are to be completed by the effective date of the standard. To the best of our knowledge, none of these assessments has been initiated at this late date. We encourage the Commission to remind NERC of its obligations under FERC Order 779 (p. 36):

> **Commission Determination**
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> 51. The Commission accepts the proposal in NERC's May 21, 2012 post-Technical Conference comments and directs NERC to "identify facilities most at-risk from severe geomagnetic disturbance" and "conduct wide-area geomagnetic disturbance vulnerability assessment" as well as give special attention to those Bulk-Power System facilities that provide service to critical and priority loads. As noted in NERC's comments, owners and operators of the Bulk-Power System, as opposed to NERC, will perform the assessments and special attention will be given to evaluating critical transformers (e.g., step-up transformers at large generating facilities).82 We agree with the Trade Associations that system-wide assessments could be conducted by planning authorities, or another functional entity with a wide-area perspective, in coordination with owners and operators of the Bulk-Power System. 83 NERC should oversee these efforts and provide responsible entities with a methodology for identifying "at-risk" Bulk-Power System components and "critical and priority loads" that need to be analyzed in the "Initial Actions.

FERC Order 779, p. 37:

> 52. Some commenters state that tools do not exist for conducting the "Initial Actions" assessments. As a result, the commenters assert that the schedule for completing the "Initial Actions" assessments is unrealistic because the commenters believe that the NOPR proposed to require the completion of such assessments by the filing date or implementation date of the First Stage GMD Reliability Standards. We clarify that the "Initial Actions" assessments do no need to be completed by the filing date or implementation date of the First Stage GMD Reliability Standards. The NOPR only proposed that the "Initial Actions" assessments should begin immediately (i.e., simultaneous with the development of the First Stage GMD Reliability Standards). Thus, the "Initial Actions" assessments provide a head start for analyzing the most at-risk and critical facilities before the Second Stage GMD Reliability Standards become effective and could be used to assist in performing the GMD vulnerability assessments required in the Second Stage GMD Reliability Standards. Further, to the extent that owners and operators of the Bulk-Power System have already begun to identify facilities most at-risk

from severe GMD events, those assessments should help to inform the "Initial Actions" assessments required by this final rule.

FERC Order 779, p. 38:

> 53. In NERC's May 21, 2012 post Technical Conference comments, NERC stated that all of its proposed "Initial Actions" would take 18-24 months to complete.84 The June 2012 GMD Task Force Phase 2 Scope and Project Plan estimated that "improve[d] tools for industry planners to develop GMD mitigation strategies" would be completed within 12-36 months, depending on the task, and "improve[d] tools for system operators to manage GMD impacts" would be completed within 12-24 months. Adjusting the deadline for submission of the Second Stage GMD Reliability Standards to 18 months allows time to identify facilities most at-risk from severe geomagnetic disturbance and to conduct wide-area geomagnetic disturbance vulnerability assessment, with special attention being given to those Bulk-Power System facilities that provide service to critical and priority loads, before the effective date of the Second Stage GMD Reliability Standards.

Lack of Due Process in NERC Standard-Setting

Oak Ridge National Laboratory estimates that a severe solar storm would interrupt power to as many as 130 million Americans. Accordingly, a reliability standard to prevent a blackout from GMD should deserve the highest level of procedural attention from NERC staff and its independent trustees.

The Foundation for Resilient Societies diligently objected to the TPL-007-1 in the NERC standard-setting process, bringing forth a Level 1 Appeal to NERC staff and a Level 2 Appeal to a subcommittee of the NERC Board of Trustees. The independent trustees of NERC should have a fiduciary duty to hear Level 2 Appeals on a timely basis and render decisions in time for the public to comment in federal rulemaking. However, as of the date we submit our comments on this docket, we have yet to learn of the disposition of our appeal, nor will we or other commentators have a citable record of our Level 2 Appeal. This is a gross violation of due process that has caused us irreparable harm in the preparation of our comments and in the federal rulemaking process.

Summary of Rationale for Remand

NERC was once a voluntary standard-setting organization, but as designated Electric Reliability Organization, it has a duty to propose standards that are technically justified. Unfortunately, with Standard TPL-007-1, NERC has failed in its duty to the Commission and to the public. Both NERC and FERC will defeat the purpose of the Energy Policy Act of 2005 if they combine a standard with barriers to hardware protection against GMD, and liability protection against negligence that diminishes a robust marketplace for higher reliability of electric service.

The substantive facts illuminated in this comment show that Standard TPL-007-1 is defectively drafted and will not protect the safety of the public, except by voluntary action outside of the requirements of the standard.

Importantly, implementation of "best practices" above minimums set in the standard may not be eligible for cost recovery and therefore are likely to be put aside. Further, by proposing liability protection in FERC Order No. 779, FERC is effectively disabling prudent underwriting by the insurance and reinsurance industries and implementation of "best practices." Instead of inspecting utility operators and rewarding through reduced insurance premiums "best practices," insurers may watch from the sidelines, constrict the scope of their underwriting, or both.

Reliability Standard TPL-007-1 is a "paper compliance" standard that establishes a Benchmark GMD Event so low, and a transformer thermal assessment Screening Criterion so high, that essentially no hardware protection will be required for nearly all power transformers exposed to GMD impacts. In return for GMD Vulnerability Assessments that will determine in most cases that no tangible action is necessary, electric utilities would claim to receive liability protection for following a federally approved reliability standard.[68]

We ask the Commission to reject this fundamentally flawed and imprudent framework for Standard TPL-007-1 that has allowed NERC and the electric utility industry to pile imprudent

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[68] Resilient Societies challenges any FERC claim of authority to grant liability protection by issuance of one or more reliability standards.

assumption on top of imprudent assumption. The result is a miasma of exemptions and inaction. The Commission should remand the entire standard TPL-007-1 to NERC for fundamental reassessment and improvements.

We also urge the Commission to seek assistance from all sources of expertise, including the Department of Defense (DOD) Defense Threat Reduction Agency (DTRA) and from the U.S. Department of Energy (DOE) National Laboratories, with the support of DOE on issues including: vibration effects (Idaho National Laboratory [INL] and DoD DTRA); interactions between installation of E1 and E2 protective hardware upon vulnerability to E3 (INL and DTRA); installation of E3 protective hardware upon E1 reduced vulnerability and mitigation cost impacts (INL and DTRA); coastal effects modeling ; GMD modeling (Los Alamos National Laboratory); and magnetotelluric modeling (USGS).

A better framework would be to require utilities to protect up to a 1-in-100 Year Reference Storm and make utilities liable for any negligence setting in geomagnetic latitude scaling factors, ground model scaling factors, transformer screening criteria, transformer thermal assessments, and other factors that could justify not installing automated and near-real-time equipment protection.

It would be far better for FERC to remand Standard TPL-007-1 than to saddle the public with a reliability standard that would grant liability protection to utilities while blocking the electric grid protection that a 21st century society requires.

Respectfully submitted by:

Thomas S. Popik, Chairman,

William R. Harris, Secretary, and
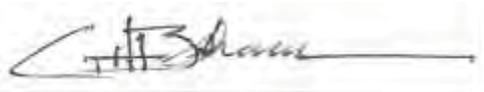
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Appendix 1

Preliminary Economic Analysis of Electric Grid Protection
Against Geomagnetic Disturbance (GMD) Events
by
Jon D. Bate[69]
Prepared for the
Foundation for Resilient Societies, Inc.
52 Technology Way
Nashua, NH 03060

Summary:

The financial impact of a severe "1-in-100 year" geomagnetic disturbance (GMD, known commonly as a "solar storm") can be estimated using a parameterized economic model. The economic model assumes that economic activity, as measured by local Gross Domestic Product (GDP) will be seriously degraded in geographic areas that experience a blackout due to GMD effects. GDP will also be affected, but much less significantly, in geographic areas usually engaged in day-to-day commerce with the "blackout region." The model additionally assumes increases in premature mortality ("loss of life") due to blackout conditions and calculates the social cost of deaths using metrics employed by the U.S. government in other cost-benefit analyses.

The economic model indicates that a severe GMD event and resulting wide-area blackout would be extremely costly, both in terms of direct economic losses and also in social cost of lives lost due to increased mortality rates. Economic losses for electric utilities are modeled separately from society as a whole. For utilities, the model assumes financial impacts are principally lost revenue during the blackout duration, as well as grid equipment damaged from GMD and/or associated system collapse.

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[69] Jon Bate, a captain in the U.S. Army, is an unpaid summer intern with the Foundation for Resilient Societies, Inc. He is a second year Master's in Public Policy candidate at the Harvard Kennedy School of Government. The analysis and views expressed do not reflect the position of the U.S. Army, any other federal department or agency, or Harvard University. The author credits the assistance of Resilient Societies staff in developing and refining the economic model.

A 2012 study by the North American Electric Reliability Corporation (NERC) hypothesized that the most likely severe GMD scenario would be system collapse due to voltage instability, with restoration times "a matter of hours to days," if replacement transformers were readily available or unnecessary in most cases.[70] An alternative report commissioned by Oak Ridge National Laboratory and sponsored by the U.S. Department of Energy, U.S. Department of Homeland Security, and Federal Energy Regulatory Commission concluded the most likely scenario is a long-term outage due to extra high voltage transformer damage, with outage periods of months or years.[71] Instead of assuming a single "correct" scenario, the economic model takes the approach of making "duration of outage" a parameter that can be adjusted to reflect the different risk perspectives and economic incentives of utilities and the general public.

Significantly, the economic model is risk-adjusted for the small probability—about 1%-- of a blackout from severe GMD in any single year; therefore, the significant cost of transformer damage for electric utilities is risk-adjusted by a factor of 0.01. However, hardware-based protective cost for transformers, assumed to be the cost of neutral ground blocking devices on a ten-year amortized basis, is modeled as a certainty, without risk adjustment.

Since private utility companies do not bear the full risk-adjusted societal cost of an outage, but only their own risk-adjusted costs, the modeling results (see Figures 1 and 2) show that they have lower economic incentive to protect against GMD events, absent subsidy, strict regulatory standards, and/or legal liability from negligence claims. In contrast, society as a whole has significant economic incentive to protect against even short-term blackouts of one day.

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[70] 2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System," NERC, February 2012, available at https://www.frcc.com/Public%20Awareness/Lists/Announcements/Attachments/105/GMD%20Interim%20Report.pdf

[71] John Kappenman. "Geomagnetic Storms and Their Impacts on the U.S. Power Grid (Meta-R-319)." Metatech. January 2010. Available from http://web.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-319.pdf.

Key Findings:

- A one-day solar storm could cause 163 million people in 25 states and Washington, D.C. to lose power (based on a 50 degree latitude, 4,800 nanoTesla/minute GMD scenario described in Metatech-R-319 report).[72]

- Societal cost of a one-day solar storm power outage is estimated at $35.7 billion (primarily due to lost GDP and loss of life), compared to $3.0 billion for first day losses for private utility companies (the first-day losses for electric utilities result primarily from transformer damage while subsequent losses would be primarily due to lost electricity revenue).[73]

- Power outage scenario results in 574 deaths per day in affected states due to a degraded healthcare system and increase in accidental deaths.

- Investing in protective equipment for at-risk transformers to avoid a one-day outage has a highly favorable benefit-cost ratio (greater than 10) from an overall social perspective.

- Private utility companies are not currently incentivized to protect against a severe GMD event unless it causes a two day outage or greater. A two-day outage would cause an estimated societal cost of $65.5 billion, including 1,147 deaths.

Modeling Assumptions:

- 25 states (and Washington, D.C.) lose power due to voltage collapse and/or permanent transformer damage: Connecticut, Delaware, Georgia, Idaho, Illinois, Indiana, Kentucky, Maine, Maryland, Massachusetts, Michigan, New Hampshire, New Jersey, New York, North Carolina, Ohio, Oregon, Pennsylvania, Rhode Island, South Carolina, Tennessee, Vermont, Virginia, Washington, West Virginia.

- GDP loss: 90% in outage states; 10% loss in non-outage states due to economic interconnectedness.

- At-risk transformer loss: 50% destruction; $5 million cost per transformer.[74]

- Loss per household due to food spoilage and other one-time costs: $48.60.[75]

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[72] Ibid.

[73] Transformer damage of $2.5 billion and residential loss of $3.4 billion are assumed to be one-time costs.

[74] Foundation for Resilient Societies estimate, based on average transformer cost

- Increase in daily mortality rate in outage states is 15%.[76] Cost per life lost: $9.1 million.[77]

- Cost of lost electric utility revenue in affected states: $519 million per day.[78]

Cost-Benefit Analysis of Protection:

Figure 1: Societal Cost-Benefit Analysis

	1 Day Outage	**2 Day Outage**
GDP Loss	$24.6 billion	$49.2 billion
Transformer Damage	$2.5 billion	$2.5 billion
Residential Losses	$3.4 billion	$3.4 billion
Number of Lives Lost	574	1,147
Social Cost of Lives Lost	$5.2 billion	$26.1 billion
Total Societal Cost	**$35.7 billion**	**$65.5 billion**
Risk-Adjusted Societal Cost	$0.36 billion	$0.66 billion
Total Protective Cost	$0.35 billion	$0.35 billion
Amortized Annual Protective Cost	$0.035 billion	$0.035 billion
Societal Benefit-Cost Ratio	**10.3**	**18.9**

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[75] Sullivan, et. al. "Estimated Value of Service Reliability for Electric Utility Customers in the United States." January 2015. http://www.osti.gov/scitech/servlets/purl/1172643. Extrapolated cost of 16 hour outage to a 24 hour period. This is a one-time loss due to loss of perishable goods and increased consumption of stored nonperishable items.

[76] Anderson and Bell. "Lights out: Impact of the August 2003 power outage on mortality in New York, NY." *Epidemiology (Cambridge, Mass)*. 2012;23(2):189-193. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3276729/. Researchers use a regression model to estimate increased mortality in the New York City metropolitan area to be 28% for a one day outage. This model uses a more conservative estimate of 15% since rural areas will be less-affected by a blackout.

   The percentage of U.S. population residing in coastal counties adjacent to the Atlantic and Pacific Oceans, the Great Lakes, and the Gulf of Mexico has increased to 29 percent of total U.S. population between the period 1960 and 2008. See the year 2010 Census Bureau report, Coastline Population Trends in the United States: 1960 to 2008. Blackout-related mortality in U.S. coastal counties and densely-populated urban areas may be substantially higher than the 15 percent estimated in this paper, while it may be substantially lower in more rural areas.

[77] "Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analyses." U.S. Department of Transportation. http://www.transportation.gov/sites/dot.dev/files/docs/VSL%20Guidance_2013.pdf

[78] "Retail Electricity Sales Statistics, 2012." Annual Electric Power Industry Report. U.S. Energy Information Administration, Form EIA-861, "Annual Electric Power Industry Report."

Figure 2: Private Utility Cost-Benefit Analysis

	1 Day Outage	2 Day Outage
Loss of Electricity Revenue	$0.52 billion	$1.0 billion
Transformer Damage	$2.5 billion	$2.5 billion
Total Private Utility Cost	**$3.0 billion**	**$3.5 billion**
Risk-Adjusted Private Utility Cost	$0.030 billion	$0.035 billion
Total Protective Cost	$0.35 billion	$0.35 billion
Amortized Annual Protective Cost	$0.035 billion	$0.035 billion
Private Utility Benefit-Cost Ratio	**0.9**	**1.0**

Cost-Benefit Analysis Assumptions:

- $350,000 cost to protect each transformer with neutral blocking equipment.[79]

- Protective equipment cost is amortized over a 10 year useful life.[80]

- Probability of severe solar storm: 1% per year (approximately)—12% per decade.[81]

Conclusions:

Due to the high societal costs of a power outage, federal and state governments have an incentive to protect against even a one-day power outage due to a GMD event. However, private utility companies do not have a business case to invest in protective transformer equipment until the projected outage reaches a minimal duration of two days, assuming there is no cost recovery for protective equipment and also assuming utilities have no exposure to losses from negligent liability claims. Utility losses due to transformer damage and lost electricity revenues are projected to be 7% to 8% of aggregate societal costs the first day of an outage.

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[79] Foundation for Resilient Societies estimate based on discussions with manufacturers of protective equipment. Only "at-risk" transformers according to Metatech R-319 report would require protection.
[80] Useful life of blocking equipment would likely exceed 10 years.
[81] Pete Riley. "On the Probability of Occurrence of Extreme Space Weather Events." February 2012. Available from http://onlinelibrary.wiley.com/doi/10.1029/2011SW000734/abstract

By the two-day mark, society faces a cost of $65.5 billion, including over 1,100 lost lives. Absent mandatory governmental regulation, the lack of incentive for private utilities to protect the grid creates a classic "market failure" for grid protection. Protecting the bulk power grid against a severe GMD event creates a positive externality that benefits our electricity-dependent society in the form of avoided power outage costs. Since private utilities do not possess sufficient incentive to invest in the socially optimal level of grid protection, the gap in protection requires government action in the form of subsidy (cost recovery for protective equipment), regulation, and/or establishment of legal liability for negligence.

Appendix 2

Reference Documents

UNITED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

Reliability Standard for Transmission System Planned	)	Docket No. RM15-11-000
Performance for Geomagnetic Disturbance Events	)	

Reference Document No. 1

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Foster, John S.; Gjelde, Earl; Graham, William R; Hermann, Robert J.; Kluepfel, Henry M.; Lawson, Richard L.; Soper, Gordon K.; Wood, Lowell L., Jr.; Woodard, Joan B.
Title	Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack: Critical National Infrastructures
Publication Series	www.empcommission.org/reports.php
Date	April 2008
Web click-through	http://www.empcommission.org/docs/A2473-EMP_Commission.pdf
Key findings	Ch. 2, Electric Power, pp. 17-61; Fig. 2-3, GIC Damage to Transformer During 1989 Geomagnetic Storm, p. 33; EMP Comm'n field tests of electrical system components and subsystems substantially less than projected EMP E3 fields, p. 18; GMD storms have caused both transformer and capacitor damage even on properly protected equipment, p. 33; 1 in 100 year GMD storm will cause "hundreds of high voltage transformers to saturate" leading to "voltage collapse in the affected areas and damage to elements of the transmission system," p. 43; likelihood of a blackout lasting years over large portions of the affected region is substantial with damage to these high-value components. The islanding … may help reduce the E2 and E3 impacts…." p. 59
Together with other relevant materials and references.	

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Reference Document No. 2

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Stockton, Paul; Beck, Chris; and Schnurr, Avi (eds.)
Title	Electric Infrastructure Protection (E-PRO) Handbook
Publication Series	www.eiscouncil.org
Date	1st ed. Dec. 17, 2014
Web click-through	Not available. Hard copies distributed 7-21-15 to FERC Commissioners and staff.
Key findings	Severe GMD durations, p. 72; ch. 2, Power Grid Protection & Restoration, pp. 89-190; E-threat characteristics, pp. 103-108; Fig. 2.3, p. 118 shows high voltage transmission systems at risk; Fig. 2.4, locations of Top 500 GIC Participation transformers in CONUS, p. 119 is inconsistent with NERC GMD benchmark model; during "very large" GMD events, transformers near coasts and in Southeast, Florida, and Gulf of Mexico are included among transformers "most likely to be at risk of excessive, > 90 Amps per phase GIC flow"; proposed selective load shedding for unprotected transformers, p. 126, may be infeasible in limited warning windows with exclusion of generator operators from EOP-010-1 mitigation duties without mandatory GIC data sharing. See pp. 132-136 on derating or disconnection options for unprotected EHV transformers. E-3 protection for GMD will benefit E3 protection for EMP; assess consequences of mitigation hardware for GMD-EMP interactions and cost impacts.
Together with other relevant materials and references.	

Reliability Standard for Transmission System Planned) Docket No. RM15-11-000
Performance   for Geomagnetic Disturbance Events)

Reference Document No. 3

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	John Kappenman for Metatech Corp. Meta R-319
Title	Geomagnetic Storms and Their Impact on the US Power Grid
Publication Series	
Date	January 2010
Web click-through	https://www.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-319.pdf
Key findings	GMD threat environment for power grid, pp. 1-1 to 1-31; March 1989 storm impacts, pp. 2-1 to 2-22; sec.2.2.5 increased reactive power demand and concurrent loss of reactive power capacity in solar storms, a missing element of NERC-FERC modeling upon risks of instability, cascading outages and grid separation, pp 2-23 to 2-28; Salem-1 damage, pp. 2-29 to 2-35; threats from extreme geomagnetic storms, pp. 3-1 to 3-30; At-risk extra high voltage transformers, pp. 4-1 to 4-23; instant reactive power demand increases, p. A1-4; App. 2, detailed Summary, Hydro-Quebec Storm, March 13-14, 1989, pp.A2-1 to A2-8; Appendix 3, Benchmarking solar storms, showing broad impacts concurrently, pp. A3-1 to A3-20; App. 4, Validating transformer modeling, pp. A4-1 to A4-23, in contrast with failure of GMD Task Force to validate its model with empirical transformer performance indicators for North America.
Together with other relevant materials and references.	

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Reference Document No. 4

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Frank Koza
Title	NERC GMD Reliability Standards
Publication Series	Idaho National Laboratory
Date	April 8, 2015
Web click-through	[Frank Koza presentation on GMD standard](#)
Key findings	
Together with other relevant materials and references.	

Reliability Standard for Transmission System Planned)   Docket No. RM15-11-000
Performance   for Geomagnetic Disturbance Events)

Reference Document No. 5

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Foundation for Resilient Societies & NERC Staff
Title	NERC Level 1 & 2 Appeal Record in TPL-007-1 Transmission System Planned Performance for Geomagnetic Disturbance Events (Project 2013-03, Geomagnetic Disturbance Mitigation.
Publication Series	
Date	January/February 2015
Web click-through	http://www.nerc.com/pa/stand/project201303geomagneticdisturbancemitigation/2013-03_gmd_level_2_appeal_foundation_for_resilient_societies_tpl-007-1_05182015.pdf. http://www.resilientsocieties.org/uploads/5/4/0/0/54008795/appeals_20150104_nerc_stage_1_appeal_tpl-007-1.pdf http://www.resilientsocieties.org/uploads/5/4/0/0/54008795/letters_20150226_nerc_stage_2_appeal_tpl-007-1.pdf
Key findings	Resilient Societies cites failures of data collection, data sharing, data validation, model validation with empirical data from North America and not Finland and other IMAGE sites in Northern Europe; and failures of quality control by the NERC Office of Standards. The failure to include model elements for Reactive Power Losses, Increased VAR demand, and potential system imbalance impacts on voltage and frequency swings; the absence of vibration modeling; the absence of a coast effect; and bias in other model components drive Benchmark Model postulates to the point that known transformer losses during solar storms – at Wiscasset, Maine (Maine Yankee); Seabrook, NH; and Salem 1 and 2 in New Jersey) and other locations of prior damaged or destroyed transformers are exempt from even "assessment" duties. Procedural failures drive substantive errors with systematic bias against any assessment duty for hardware protection.
Together with other relevant materials and references.	

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Reference Document No. 6

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Central Maine Power Co., by Justin Michlig, with contributions by Emprimus, Maine Public Utilities Commission, et al.
Title	2014 Maine GMD/EMP Impacts Assessment
Publication Series	Maine Public Utilities Commission Filings in MPUC Docket 2013-00415
Date	December 23, 2014
Web click-through	https://www.mpuc-cms.maine.gov. Lookup Docket 2013-00415. Download item 51.
Key findings	GIC has potential to cause disruption to power system operations, by transformer heating, reduced voltage operations and harmonics. p.6. The NERC Benchmark model adjusted for Northern Maine projects maximum of 4.53 volt/km geoelectric field for NERC's claimed 1 in 100 year benchmark storm. p.7. The CMP Study Team assumed 1 in 50 year storm voltage up to 14 volts/km and 1 in 100 year volts/km up to 23.5 volts, p.7. Using the NERC model, no neutral blocking devices or other mitigation hardware would be required in Maine. The 1 in 50 yr storm per CMP modeling would justify $2.8 M of neutral ground blocking for 7 transformers at $350K per unit; 16 GIC monitors, at per unit installed cost of $36K. Susceptible capacitor replacements would cost $1M for 4 capacitors. p.7. Since publication in Dec. 2014 and NERC proposed GMD Hardware standard in Jan. 2015, Central Maine Power has declined to budget for or order protective equipment including neutral ground blockers, despite CMP finding 7 of its transformers would exceed 75 Amps per Phase for both their 1 in 50 year GMD event, and their 1 in 100 year GMD event. See Table 3 at p. 27. These results do not model a "coastal effect" which would place at risk additional transformers, and which may have caused damage to Maine Yankee's GSU 345 kV transformer in March 1989 GMD, loss of that transformer in April 1991 and potential damage to 2 replacement GSU transformers installed in 1993.
Together with other relevant materials and references.	

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Reference Document No. 7

Submitted by the Foundation for Resilient Societies

52 Technology Way, Nashua, NH 03060

in FERC Docket No. RM15-11-000

(filed on July 27, 2015)

Author(s)	Emprimus
Title	Effects of GMD and EMP on the State of Maine Power Grid
Publication Series	
Date	January 2, 2015
Web click-through	http://www.maine.gov/tools/whatsnew/attach.php?id=639058&an=2
Key findings	
Together with other relevant materials and references.	

Reliability Standard for Transmission System Planned)   Docket No. RM15-11-000
Performance   for Geomagnetic Disturbance Events)

Reference Document No. 8

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Foundation for Resilient Societies
Title	Economic Model for Mitigation of GMD and EMP
Publication Series	
Date	2015
Web click-through	Resilient Societies EMP GMD Cost Estimate
Key findings	
Together with other relevant materials and references.	

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Reference Document No. 9

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Dr. David Boteler
Title	The impact of space weather on the electric power grid
Publication Series	Heliophysics V. Space Weather and Society
Date	July 7, 2014
Web click-through	http://www.spacewx.net/pdf/HSS5.pdf pp 68-89
Key findings	
Together with other relevant materials and references.	

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Reference Document No. 10

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Carolus J. Schrijver & Sarah D. Mitchell
Title	Disturbances in the US electric grid associated with GMD
Publication Series	J. Space Weather Space Climate
Date	April 19, 2013
Web click-through	http://www.swsc-journal.org/articles/swsc/pdf/2013/01/swsc120066.pdf
Key findings	For the period 1992 thru 2010, with more than 3σ **(sigma)** significance, or odds ratio of 32-to-1, approximately 4% of disturbances in the U.S. power grid reported to the US Department of Energy "are attributable to strong geomagnetic activity and associated geomagnetically induced currents." Abstract. GICs induce thermal effects and reactive power consumption that impacts regional reactive power imbalance s with swings in voltage and frequency. A19p1. Mitigation strategies are warranted. A19p7.
Together with other relevant materials and references.	

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Reference Document No. 11

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Lloyd's; Atmospheric & Environmental Research
Title	Solar Storm Risk to the North American Electric Grid
Publication Series	
Date	2013
Web click-through	Lloyds & AER Report
Key findings	
Together with other relevant materials and references.	

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Performance　for Geomagnetic Disturbance Events　　　)

Reference Document No. 12

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Lloyd's
Title	The insurance implications of a cyber attack on the US power grid
Publication Series	Emerging Risk Report – Innovation Series
Date	July 2015
Web click-through	Lloyds Business Blackout Report
Key findings	
Together with other relevant materials and references.	

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Reference Document No. 13

Submitted by the Foundation for Resilient Societies

52 Technology Way, Nashua, NH 03060

in FERC Docket No. RM15-11-000

(filed on July 27, 2015)

Author(s)	C.J. Schrijver, R. Dobbins, W. Murtagh, S.M. Petrinec
Title	Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment
Publication Series	Space Weather Journal
Date	June 21, 2014
Web click-through	http://arxiv.org/pdf/1406.7024v1.pdf
Key findings	
Together with other relevant materials and references.	

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Performance   for Geomagnetic Disturbance Events   )

<u>**Reference Document No. 14**</u>

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	National Security Telecommunications Advisory Committee
Title	NSTAC Issue Review 06-07
Publication Series	
Date	2007
Web click-through	http://www.dhs.gov/sites/default/files/publications/2006-2007%20NSTAC%20Issue%20Review_0.pdf
Key findings	
Together with other relevant materials and references.	

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Reference Document No. 15

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Scott Dahman, PowerWorld Corporation
Title	BPA GMD Impact Assessment TIP 264 GIC R&D
Publication Series	
Date	September 30, 2013
Web click-through	http://elibrary.ferc.gov/idmws/common/opennat.asp?fileID=13941706
Key findings	Modeling for voltage collapse.
Together with other relevant materials and references.	

Exhibit Q

"Benchmark Geomagnetic Disturbance Event Description"
Project 2013-03. GMD Mitigation Standard Drafting Team. May 12, 2016.

Benchmark Geomagnetic Disturbance Event Description

Project 2013-03 GMD Mitigation
Standard Drafting Team
May 12, 2016

RELIABILITY | ACCOUNTABILITY

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Preface

The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to ensure the reliability of the Bulk-Power System (BPS) in North America. NERC develops and enforces Reliability Standards; annually assesses seasonal and long-term reliability; monitors the BPS through system awareness; and educates, trains, and certifies industry personnel. NERC's area of responsibility spans the continental United States, Canada, and the northern portion of Baja California, Mexico. NERC is the electric reliability organization (ERO) for North America, subject to oversight by the Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada. NERC's jurisdiction includes users, owners, and operators of the BPS, which serves more than 334 million people.

The North American BPS is divided into several assessment areas within the eight Regional Entity (RE) boundaries, as shown in the map and corresponding table below.
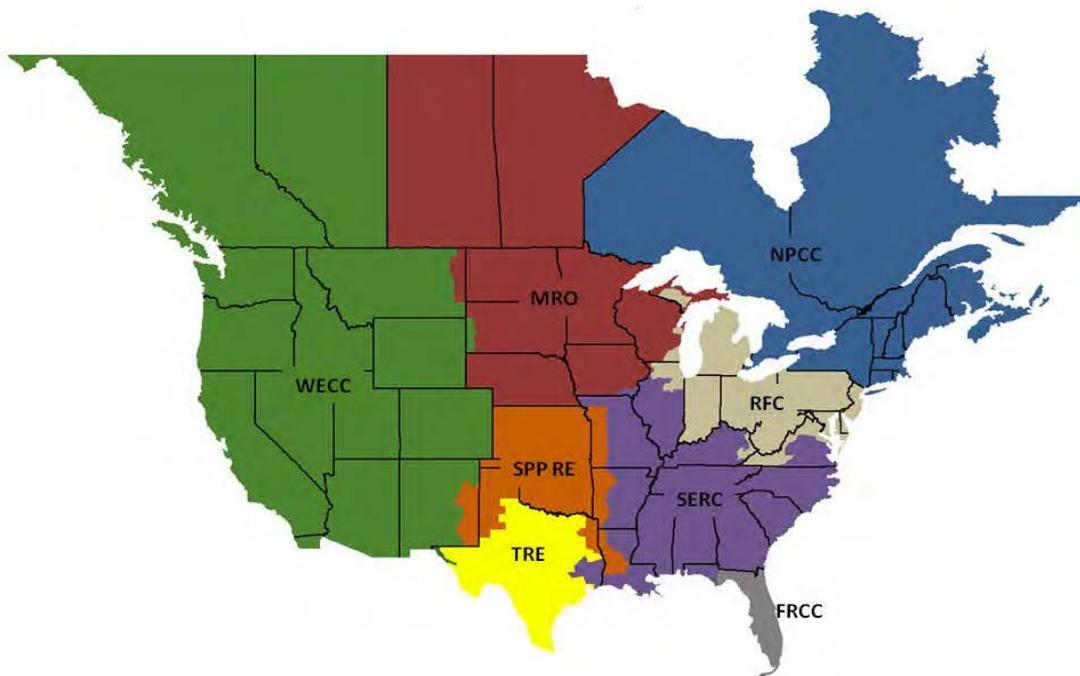
FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RFC	Reliability*First* Corporation
SERC	SERC Reliability Corporation
SPP-RE	Southwest Power Pool Regional Entity
TRE	Texas Reliability Entity
WECC	Western Electric Coordinating Council

Introduction

Background

The purpose of the benchmark geomagnetic disturbance (GMD) event description is to provide a defined event for assessing system performance during a low probability, high magnitude GMD event as required by proposed standard TPL-007-1 – Transmission System Planned Performance for Geomagnetic Disturbance Events. The benchmark GMD event defines the geoelectric field values used to compute geomagnetically-induced current (GIC) flows for a GMD Vulnerability Assessment.

On May 16, 2013, FERC issued Order No. 779, directing NERC to develop Standards that address risks to reliability caused by geomagnetic disturbances in two stages:

- Stage 1 Standard(s) that require applicable entities to develop and implement Operating Procedures. EOP-010-1 – Geomagnetic Disturbance Operations was approved by FERC in June 2014.
- Stage 2 Standard(s) that require applicable entities to conduct assessments of the potential impact of benchmark GMD events on their systems. If the assessments identify potential impacts, the Standard(s) will require the applicable entity to develop and implement a plan to mitigate the risk.

TPL-007-1 is a new Reliability Standard developed to specifically address the Stage 2 directives in Order No. 779. The benchmark GMD event will define the scope of the Stage 2 Reliability Standard.

General Characteristics

The benchmark GMD event described herein takes into consideration the known characteristics of a severe GMD event and its impact on an interconnected transmission system. These characteristics include:

- Geomagnetic Latitude – The amplitude of the induced geoelectric field for a given GMD event is reduced as the observation point moves away from the earth's magnetic poles.
- Earth Conductivity – The amplitude and phase of the geoelectric field depends on the local or regional earth ground resistivity structure. Higher geoelectric field amplitudes are induced in areas of high resistivity.
- Transformer Electrical Response – Transformers can experience half-cycle saturation when subjected to GIC. Transformers under half-cycle saturation absorb increased amounts of reactive power (var) and inject harmonics into the system. However, half-cycle saturation does not occur instantaneously and depends on the electrical characteristics of the transformer and GIC amplitude [1]. Thus, the effects of transformer reactive power absorption and harmonic generation do not occur instantaneously, but instead may take up to several seconds. It is conservative, therefore, to assume that the effects of GIC on transformer var absorption and harmonic generation are instantaneous.
- Transformer Thermal Effects (e.g. hot spot transformer heating) – Heating of the winding and other structural parts can occur in power transformers during a GMD event. However, the thermal impacts are not instantaneous and are dependent on the thermal time constants of the transformer. Thermal time constants for hot spot heating in power transformers are in the 5-20 minute range.
- Geoelectric Field Waveshape – The geoelectric field waveshape has a strong influence on the hot spot heating of transformer windings and structural parts since thermal time constants of the transformer and time to peak of storm maxima are both on the order of minutes. The frequency content of the magnetic field (dB/dt) is a function of the waveshape, which in turn has a direct effect on the geoelectric field since the earth response to external dB/dt is frequency-dependent.
- Wide Area Geomagnetic Phenomena – The influence of GMD events is typically over a very broad area (e.g. continental scale); however, there can be pockets or very localized regions of enhanced geomagnetic activity. Since geomagnetic disturbance impacts within areas of influence of approximately 100-200 km do not have a widespread impact on the interconnected transmission system (see Appendix I), statistical methods used to assess the frequency of occurrence of a severe GMD event need to consider broad geographical regions to avoid bias caused by spatially localized geomagnetic phenomena.

Benchmark GMD Event Description

Severe geomagnetic disturbance events are high-impact, low-frequency (HILF) events [2]; thus, any benchmark event should consider the probability that the event will occur, as well as the impact or consequences of such an event. The benchmark event is composed of the following elements: 1) a reference peak geoelectric field amplitude (V/km) derived from statistical analysis of historical magnetometer data; 2) scaling factors to account for local geomagnetic latitude; 3) scaling factors to account for local earth conductivity; and 4) a reference geomagnetic field time series or waveshape to facilitate time-domain analysis of GMD impact on equipment.

Reference Geoelectric Field Amplitude

The reference geoelectric field amplitude was determined through statistical analysis using the plane wave method [3]-[10] geomagnetic field measurements from geomagnetic observatories in northern Europe [11] and the reference (Quebec) earth model shown in **Table 1** [12]. For details of the statistical considerations, see Appendix I. The Quebec earth model is generally resistive and the geological structure is relatively well understood.

Table 1: Reference earth model (Quebec)	
Thickness (km)	**Resistivity (Ω-m)**
15	20,000
10	200
125	1,000
200	100
∞	3

The statistical analysis (see Appendix II) resulted in a conservative peak geoelectric field amplitude of approximately 8 V/km. For steady-state GIC and load flow analysis, the direction of the geoelectric field is assumed to be variable meaning that it can be in any direction (Eastward, Northward, or a vectorial combination thereof).

The frequency of occurrence of this benchmark GMD event is estimated to be approximately 1 in 100 years (see Appendix I). The selected frequency of occurrence is consistent with utility practices where a design basis frequency of 1 in 50 years is currently used as the storm return period for determining wind and ice loading of transmission infrastructure [13], for example.

The regional geoelectric field peak amplitude, E_{peak}, to be used in calculating GIC in the GIC system model can be obtained from the reference value of 8 V/km using the following relationship

$$E_{peak} = 8 \times \alpha \times \beta \text{ (V/km)} \tag{1}$$

where α is the scaling factor to account for local geomagnetic latitude, and β is a scaling factor to account for the local earth conductivity structure (see Appendix II).

Reference Geomagnetic Field Waveshape

The reference geomagnetic field waveshape was selected after analyzing a number of recorded GMD events, including the reference storm of the NERC interim report of 2012 [14], measurements at the Nurmijarvi (NUR) and Memanbetsu (MMB) geomagnetic observatories for the "Halloween event" of October 29-31, 2003, and the March 1989 GMD event that caused the Hydro Quebec blackout. The geomagnetic field measurement record of the March 13-14 1989 GMD event, measured at NRCan's Ottawa geomagnetic observatory, was selected as the

reference geomagnetic field waveform because it provides generally conservative results when performing thermal analysis of power transformers (see Appendix I). The reference geomagnetic field waveshape is used to calculate the GIC time series, GIC(t), required for transformer thermal impact assessment.

The geomagnetic latitude of the Ottawa geomagnetic observatory is 55°; therefore, the amplitude of the geomagnetic field measurement data were scaled up to the 60° reference geomagnetic latitude (see **Figure 1**) such that the resulting peak geoelectric field amplitude computed using the reference earth model was 8 V/km (see **Figures 2** and **3**). Sampling rate for the geomagnetic field waveshape is 10 seconds.
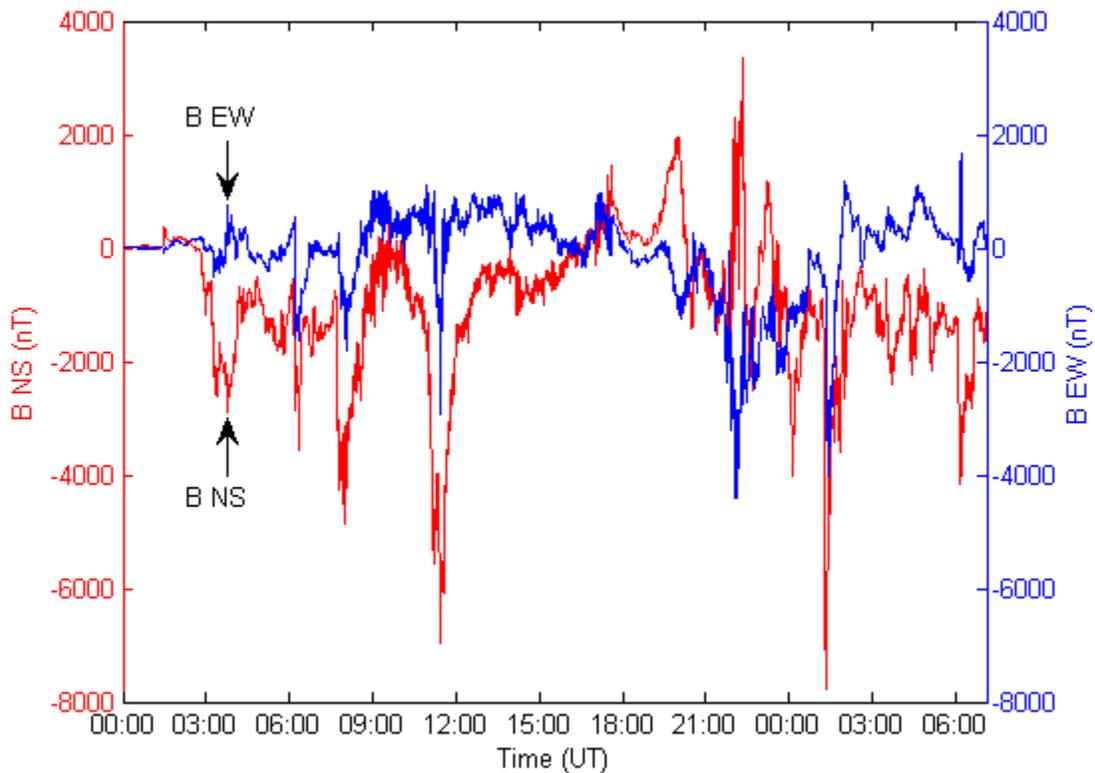
Figure 1: Benchmark Geomagnetic Field Waveshape
Red Bn (Northward), Blue Be (Eastward)
Referenced to pre-event quiet conditions
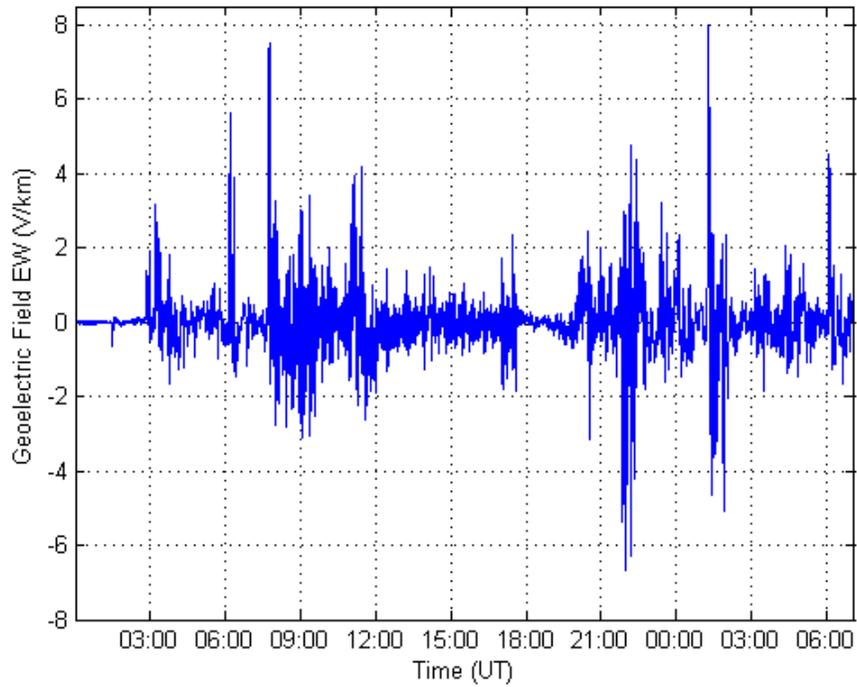
Figure 2: Benchmark Geoelectric Field Waveshape (E$_E$ Eastward)
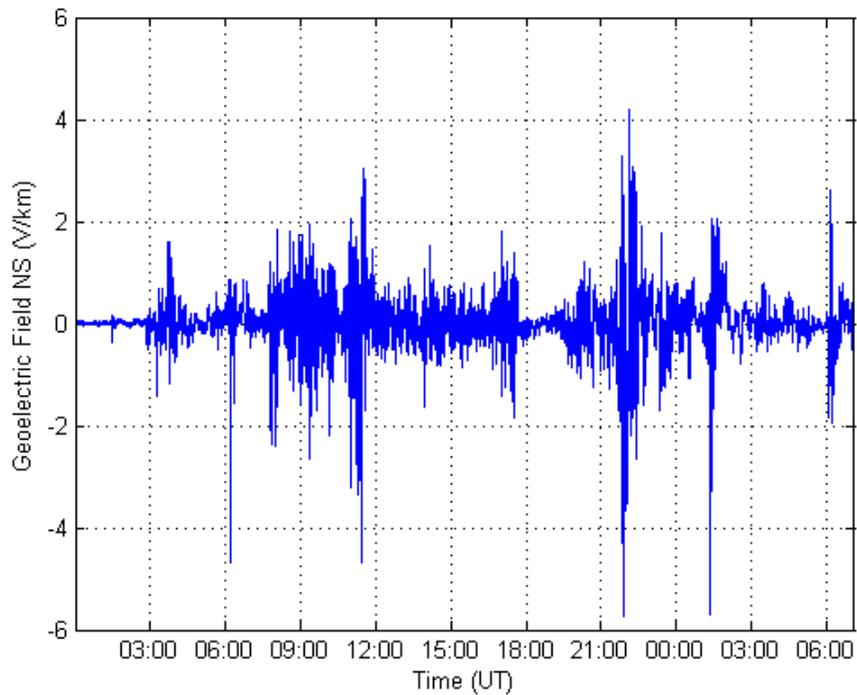
Figure 3: Benchmark Geoelectric Field Waveshape (E$_N$ Northward)

Appendix I – Technical Considerations

The following sections describe the technical justification of the assumptions that were made in the development of the benchmark GMD event.

Statistical Considerations

Due to the lack of long-term accurate geomagnetic field observations, assigning probabilities to the occurrence of historical extreme geomagnetic storms is difficult because of the lack of high fidelity geomagnetic recordings of events prior to the 1980s. This is particularly true for the Carrington event for which data that allow the direct determination of the geoelectric fields experienced during the storm are not available [15].

The storm-time disturbance index Dst has often been used as a measure of storm strength even though it does not provide a direct correspondence with GIC[1]. One of the reasons for using Dst in statistical analysis is that Dst data are available for events occurring prior to 1980. Extreme value analysis of GMD events, including the Carrington, September 1859 and March 1989 events, has been carried out using Dst as an indicator of storm strength. In one such study [16], the (one sigma) range of 10-year occurrence probability for another March 1989 event was estimated to be between 9.4-27.8 percent. The range of 10-year occurrence probability for Carrington event in Love's analysis is 1.6-13.7 percent. These translate to occurrence rates of approximately 1 in 30-100 years for the March 1989 event and 1 in 70-600 years for the Carrington event. The error bars in such analysis are significant, however, it is reasonable to conclude that statistically the March 1989 event is likely more frequent than 1-in-100 years and the Carrington event is likely less frequent than 1-in-100 years.

The benchmark GMD event is based on a 1 in 100 year frequency of occurrence which is a conservative design basis for power systems. Also, the benchmark GMD event is not biased towards local geomagnetic field enhancements, since it must address wide-area effects in the interconnected power system. Therefore, the use of Dst-based statistical considerations is not adequate in this context and only relatively modern data have been used.

The benchmark GMD event is derived from modern geomagnetic field data records and corresponding calculated geoelectric field amplitudes. Using such data allows rigorous statistical analysis of the occurrence rates of the physical parameter (i.e. rate of change in geomagnetic field, dB/dt) directly related to the geoelectric field. Geomagnetic field measurements from the IMAGE magnetometer chain for 1993-2013 have been used to study the occurrence rates of the geoelectric field amplitudes.

With the use of modern data it is possible to avoid bias caused by localized geomagnetic field enhancements. The spatial structure of high-latitude geoelectric fields can be very complex during strong geomagnetic storm events [17]-[18]. One reflection of this spatial complexity is localized geomagnetic field enhancements that result in high amplitude geoelectric fields in regions of a few hundred kilometers or less. **Figure I-1**[2] illustrates this spatial complexity of the storm-time geoelectric fields. In areas indicated by the bright red location, the geoelectric field can be a factor of 2-3 larger than at neighboring locations. Localized geomagnetic phenomena should not be confused with local earth structure/conductivity features that result in consistently high geoelectric fields (e.g., coastal effects). Localized field enhancements can occur at any region exposed to auroral ionospheric electric current fluctuations.

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[1] Dst index quantifies the amplitude of the main phase disturbance of a magnetic storm. The index is derived from magnetic field variations recorded at four low-latitude observatories. The data is combined to provide a measure of the average main-phase magnetic storm amplitude around the world.

[2]**Figure I-1** is for illustration purposes only, and is not meant to suggest that a particular area is more likely to experience a localized enhanced geoelectric field.
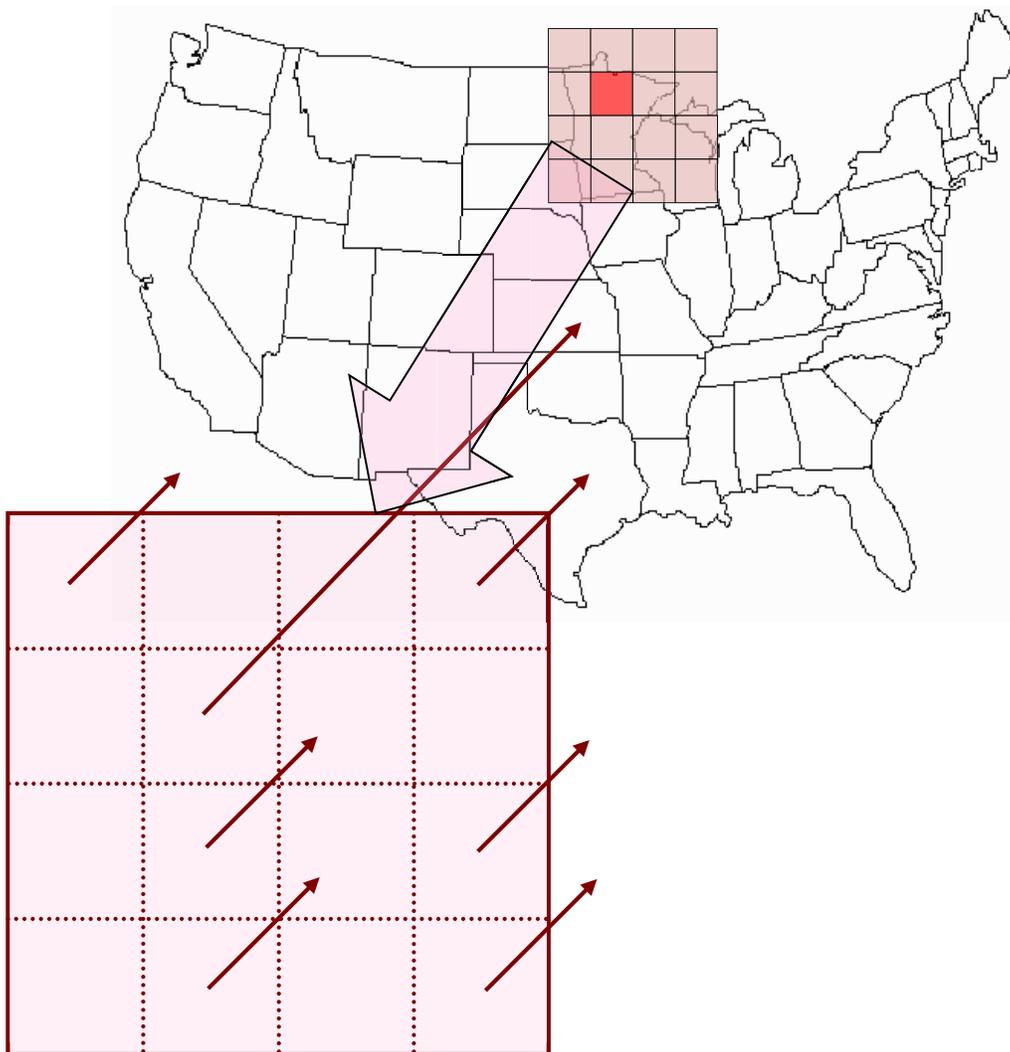
Figure I-1: Illustration of the Spatial Scale between Localized Enhancements and Larger Spatial Scale Amplitudes of Geoelectric Field Observed during a Strong Geomagnetic Storm.
In this illustration, the red square illustrates a spatially localized field enhancement.

The benchmark event is designed to address <u>wide-area</u> effects caused by a severe GMD event, such as increased var absorption and voltage depressions. Without characterizing GMD on regional scales, statistical estimates could be weighted by local effects and suggest unduly pessimistic conditions when considering cascading failure and voltage collapse. It is important to note that most earlier geoelectric field amplitude statistics and extreme amplitude analyses have been built for individual stations thus reflecting only localized spatial scales [10], [19]-[22]. A modified analysis is required to account for geoelectric field amplitudes at larger spatial scales. Consequently, analysis of spatially averaged geoelectric field amplitudes is presented below.

Figure I-2 shows statistical occurrence of spatially averaged high latitude geoelectric field amplitudes for the period of January 1, 1993 – December 31, 2013. The geoelectric field amplitudes were calculated using 10-s IMAGE magnetometer array observations and the Quebec ground conductivity model, which is used as a reference in the benchmark GMD event. Spatial averaging was carried out over four different station groups spanning a square area of approximately 500 km in width. For the schematic situation in **Figure I-1** the averaging process involves taking the average of the geoelectric field amplitudes over all 16 points or squares.

As can be seen from **Figure I-2**, the computed spatially averaged geoelectric field amplitude statistics indicate the 1-in-100 year amplitude is approximately between 3-8 V/km. Using extreme value analysis as described in the next section, it can be shown that the upper limit of the 95% confidence interval for a 100-year return level is more precisely 5.77 V/km.
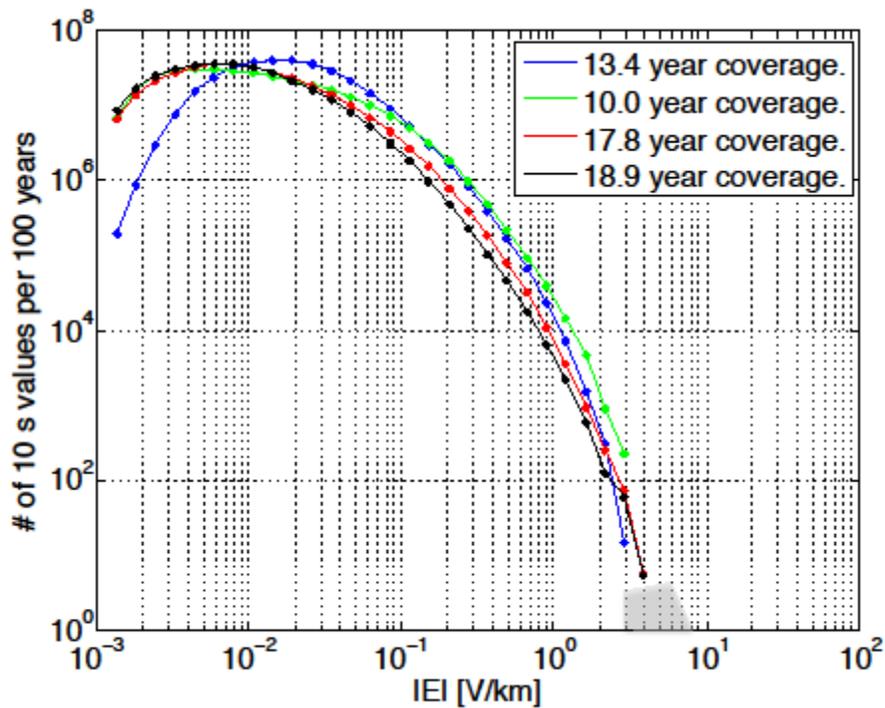

Figure I-2: Statistical Occurrence of Spatially Averaged Geoelectric Field Amplitudes.
Four curves with dots correspond to different station groups and the gray area shows a visual extrapolation to 1-in-100 year amplitudes. The legend shows the data coverage for each station group used in computing the averaged geoelectric field amplitudes.

Extreme Value Analysis

The objective of extreme value analysis is to describe the behavior of a stochastic process at extreme deviations from the median. In general, the intent is to quantify the probability of an event more extreme than any previously observed. In particular, we are concerned with estimating the 95 percent confidence interval of the maximum geoelectric field amplitude to be expected within a 100-year return period.[3] In the context of this document, extreme value analysis has been used to rigorously support the extrapolation estimates used in the statistical considerations of the previous section.

The data set consists of 21 years of daily maximum geoelectric field amplitudes derived from the IMAGE magnetometer chain, using the Quebec earth model as reference. **Figure I-3** shows a scatter plot of the 10-largest geoelectric field amplitudes per year across the IMAGE stations. The plot indicates that both the amplitude and standard deviation of extreme geoelectric fields are not independent of the solar cycle. The data clearly exhibits heteroskedasticity[4] and an 11-year seasonality in the mean.
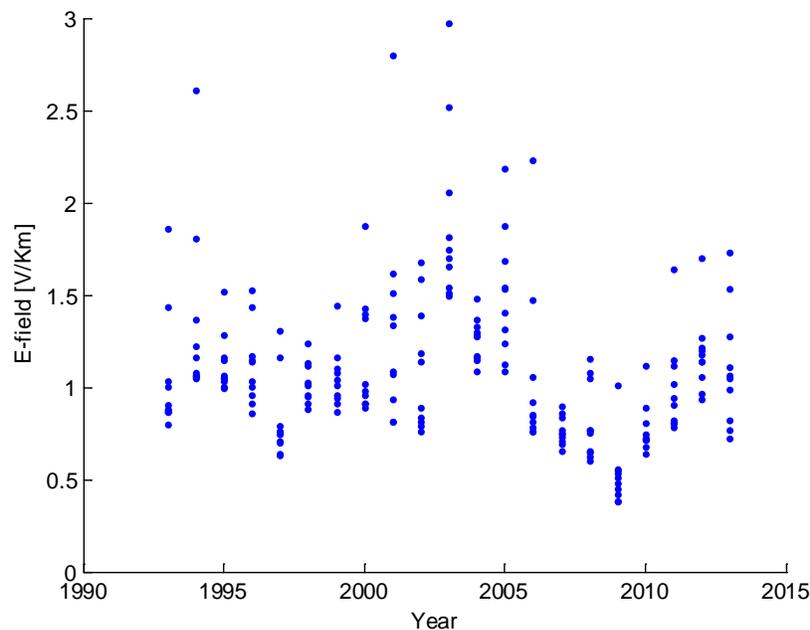
Figure I-3: Scatter Plot of Ten Largest Geoelectric Fields per Year
Data source: IMAGE magnetometer chain from 1993-2013

Several statistical methods can be used to conduct extreme value analysis. The most commonly applied include: Generalized Extreme Value (GEV), Point Over Threshold (POT), R-Largest, and Point Process (PP). In general, all methods assume independent and identically distributed (iid) data [23].

Two of these methods, GEV and POT, have been applied to the geoelectric field data, and their suitability for this application has been examined. **Table I-1** shows a summary of the estimated parameters and return levels obtained from GEV and POT methods. The parameters were estimated using the Maximum Likelihood Estimator (MLE). Since the distribution parameters do not have an intuitive interpretation, the expected geoelectric field amplitude for a 100-year return period is also included in **Table I-1.** The 95 percent confidence interval of the 100-year return level was calculated using the delta method and the profile likelihood. The delta method relies on the

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[3] A 95 percent confidence interval means that, if repeated samples were obtained, the return level would lie within the confidence interval for 95 percent of the samples.
[4] Heteroskedasticity means that the skedastic function depends on the values of the conditioning variable; i.e., $var(Y|X=x) = f(x)$.

Gaussian approximation to the distribution of the MLE; this approximation can be poor for long return periods. In general, the profile likelihood provides a better description of the return level.

Table I-1: Extreme Value Analysis

Statistical Method	Estimated Parameters	Hypothesis Testing	100 Year Return Level		
			Mean [V/km]	95% CI [V/km]	95% CI P-Likelihood [V/km]
(1) GEV	μ=1.4499 (0.1090) σ=0.4297 (0.0817) ξ=0.0305 (0.2011)	H0: ξ=0 $p = 0.877$	3.57	[1.77 , 5.36]	[2.71, 10.26]
(2) GEV $\mu = \beta_0 + \beta_1 \cdot \sin\left(\dfrac{t}{T} + \phi\right)$	β_0=1.5047 (0.0753) β_1=0.3722 (0.0740) σ=0.2894 (0.0600) ξ=0.1891 (0.2262)	H0: β_1=0 p= 0.0003 H0: ξ=0 $p = 0.38$	4	[2.64, 4.81]	[2.92, 12.33]
(3) POT, threshold=1V/km	σ=0.3163 (0.0382) ξ=0.0430 (0.0893)		3.4	[2.28, 4.52]	[2.72,5.64]
(4) POT, threshold=1V/km $\sigma = \alpha_0 + \alpha_1 \cdot \sin\left(\dfrac{t}{T} + \phi\right)$	α_0=0.2920 (0.0339) α_1=0.1660 (0.0368) ξ=-0.0308 (0.0826)	H0: α_1=0 p= 3.7e-5	3.724	[2.64, 4.81]	[3.02, 5.77]

Statistical model (1) in **Table I-1** is the traditional GEV estimation using blocks of 1 year maxima; i.e., only 21 data points are used in the estimation. The mean expected amplitude of the geoelectric field for a 100-year return level is 3.57 V/km. Since GEV works with blocks of maxima, it is typically regarded as a wasteful approach. This is reflected in the comparatively large confidence intervals: [1.77, 5.36] V/km for the delta method and [2.71, 10.26] V/km for the profile likelihood.

As discussed previously, GEV assumes that the data is iid. Based on the scatter plot shown in **Figure 1-3**, the iid statistical assumption is not warranted by the data. Statistical model (2) in **Table I-1** is a re-parameterization of the GEV distribution contemplating the 11-year seasonality in the mean,

$$\mu = \beta_0 + \beta_1 \cdot \sin\left(\frac{t}{T} + \phi\right)$$

where β_0 represents the offset in the mean, β_1 describes the 11-year seasonality, T is the period (11 years), and ϕ is a constant phase shift.

A likelihood ratio test is used to test the hypothesis that β_1 is zero. The null hypothesis, H0: β_1=0, is rejected with a p-value of 0.0003; as expected, the 11-year seasonality has explanatory power. The blocks of maxima during the solar minimum are better represented in the re-parameterized GEV. The benefit is an increase in the mean return

level to 4 V/km and a wider confidence interval: [2.63, 4.81] V/km for the delta method and [2.92, 12.33] V/km for the profile likelihood (calculated at solar maximum).

Statistical model (3) in **Table I-1** is the traditional POT estimation using a threshold u of 1 V/km; the data was de-clustered using a 1-day run. The data set consists of normalized excesses over a threshold, and therefore, the sample size for POT is increased if more than one extreme observation per year is available (in the GEV approach, only the maximum observation over the year was taken; in the POT method, a single year can have multiple observations over the threshold). The selection of the threshold u is a compromise between bias and variance. The asymptotic basis of the model relies on a high threshold; a threshold that is too low will likely lead to bias. On the other hand, a threshold that is too high will reduce the sample size and result in high variance. The stability of parameter estimates can guide the selection of an appropriate threshold. **Figure I-4** shows the estimated parameters (modified scale $\sigma^* = \sigma_u - \xi \cdot u$, and shape ξ) for a range of thresholds. The objective is to select the lowest threshold for which the estimates remain near constant; 1V/km appears to be a good choice.

The mean return level for statistical model (3), 3.4 V/km, is similar to the GEV estimates. However, due to the larger sample size, the POT method is more efficient, and consequently, the confidence intervals are significantly reduced: [2.28, 4.52] V/km for the delta method, and [2.72, 5.64] V/km for the profile likelihood method.

In order to cope with the heteroskedasticity exhibited by the data, a re-parameterization of POT is used in statistical model (4) in **Table I-1**,

$$\sigma = \alpha_0 + \alpha_1 \cdot \sin\left(\frac{t}{T} + \phi\right)$$

where α_0 represents the offset in the standard deviation, α_1 describes the 11-year seasonality, T is the period (365.25 · 11), and ϕ is a constant phase shift.

The parameter α_1 is statistically significant; the null hypothesis, H0: $\alpha_1 = 0$, is rejected with a p-value of 3.7e-5. The mean return level has slightly increased to 3.72 V/km. The upper limit of the confidence interval, calculated at solar maximum, also increases: [2.63, 4.81] V/km for the delta method and [3.02, 5.77] V/km for the profile likelihood method. As a final remark, it is emphasized that the confidence interval obtained using the profile likelihood is preferred over the delta method. **Figure I-5** shows the profile likelihood of the 100-year return level of statistical model (4). Note that the profile likelihood is highly asymmetric with a positive skew, rendering a larger upper limit for the confidence interval. Recall that the delta method assumes a normal distribution for the MLEs, and therefore, the confidence interval is symmetric around the mean.

To conclude, traditional GEV (1) and POT (3) models are misspecified; the statistical assumptions (iid) are not warranted by the data. The models were re-parameterized to cope with heteroskedasticity and the 11-year seasonality in the mean. Statistical model (4) better utilizes the available extreme measurements and it is therefore preferred over statistical model (2). The upper limit of the 95 percent confidence interval for a 100-year return level is 5.77 V/km. This analysis is consistent with the selection of a geoelectric field amplitude of 8 V/km for the 100-year GMD benchmark. .
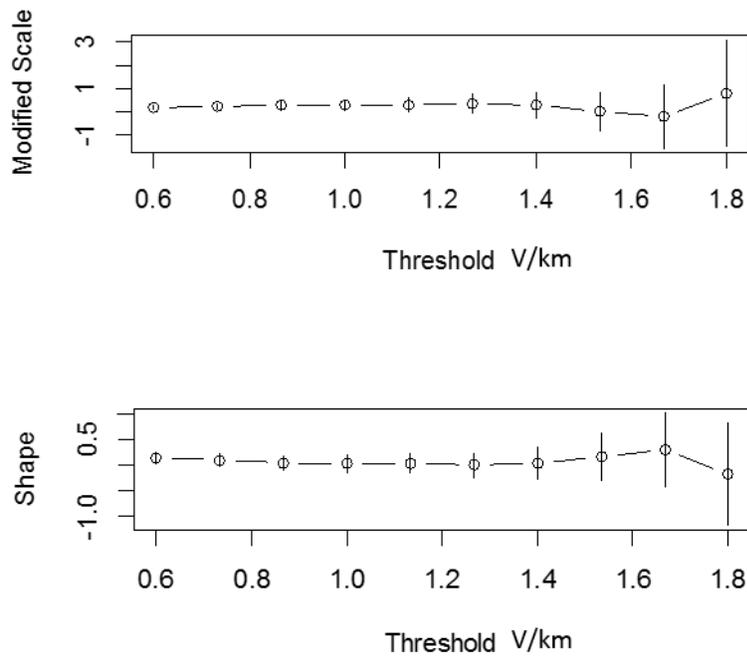
Figure I-4: Parameter Estimates Against Threshold for Statistical Model (3)
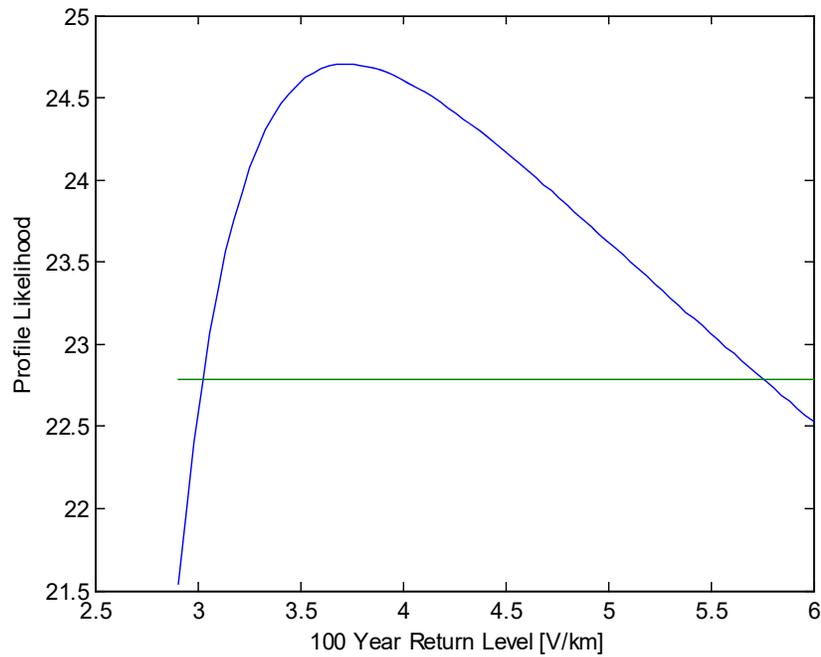

Figure I-5: Profile Likelihood for 100-year Return Level for Statistical Model (4)

Impact of Local Geomagnetic Disturbances on GIC

The impact of local disturbances on a power network is illustrated with the following example. A 500 km by 500 km section of a North American transmission network is subdivided into 100 km by 100 km sections. The geoelectric field is assumed to be uniform within each section. The analysis is performed by scaling the geoelectric field in each section individually by an intensification factor of 2.5 and computing the corresponding GIC flows in the network, resulting in a total of 25 GIC distribution simulations.[5] In these simulations the peak geomagnetic field amplitude has been scaled according to geomagnetic latitude of the network under study.

Figure I-6 shows the number of transformers that experience a GIC increase greater than 10 Amps (in red), those that experienced a reduction in GIC of more than 10 Amps (in blue), and those that remain essentially the same (in green). It can be observed that there is a small set of transformers that are affected by the local amplification of the geo-electric field but that the impact on the GIC distribution of the entire network due to a local intensification of the geoelectric field in a "local peak" is minor. Therefore, it can be concluded that the effect of local disturbances on the larger transmission system is relatively minor and does not warrant further consideration in network analysis.
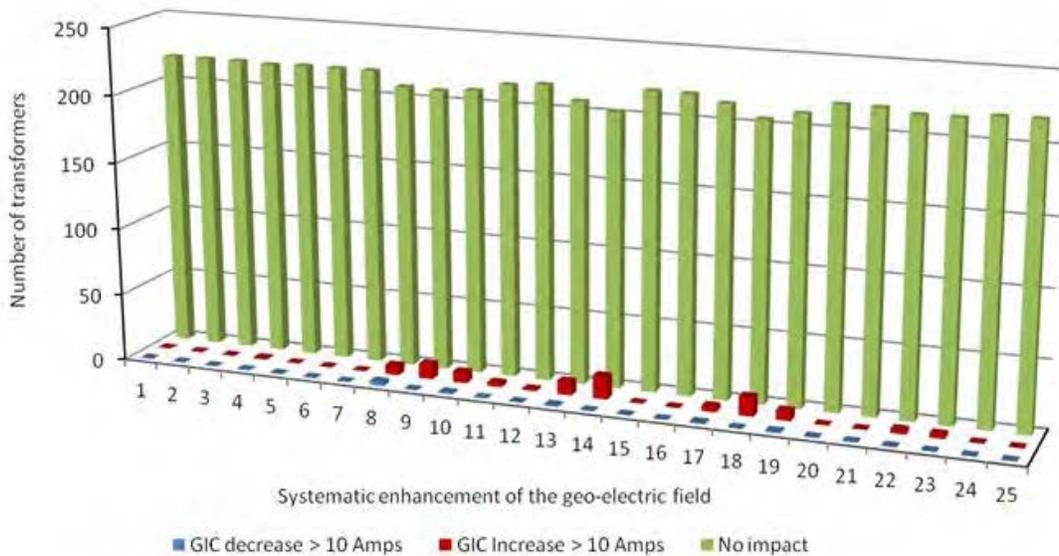

Figure I-6: Number of Transformers that see a 10 A/phase Change in GIC due to Local Geoelectric Field Intensification

Impact of Waveshape on Transformer Hot-spot Heating

Thermal effects (e.g. hot spot transformer heating) in power transformers are not instantaneous. Thermal time constants associated with hot spot heating in power transformers are in the 5-20 minute range; therefore, the waveshape of the geomagnetic and geoelectric field has a strong impact on transformer hot spot heating of windings and metallic parts since thermal time constants are of the same order of magnitude as the time-to-peak of storm maxima. The waveshape of the March 13-14 1989 GMD event measured at the Ottawa geomagnetic observatory was found to be a conservative choice when compared with other events of the last 20 years, such

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[5] An intensification factor of 2.5 would make a general 8 V/km peak geoelectric field in the entire network show a 20 V/km intensified geoelectric field in one of the twenty five 100 km by 100 km sections.

as the measurements at the Nurmijarvi (NUR) and Memanbetsu (MMB) geomagnetic observatories for the "Halloween event" of October 29-31, 2003 described in the NERC GMD interim report of 2012 [14].

To illustrate, the results of a thermal analysis performed on a relatively large test network with a diverse mix of circuit lengths and orientations is provided in **Figures I-7** and **I-8**. **Figure I-9** shows a more systematic way to compare the relative effects of storm waveshape on the thermal response of a transformer. It shows the results of 33,000 thermal assessments for all combinations of effective GIC due to circuit orientation (similar **to Figures I-7** and **I-8** but systematically taking into account all possible circuit orientations). These results illustrate the relative effect of different waveshapes in a broad system setting and should not be interpreted as a vulnerability assessment of any particular network.
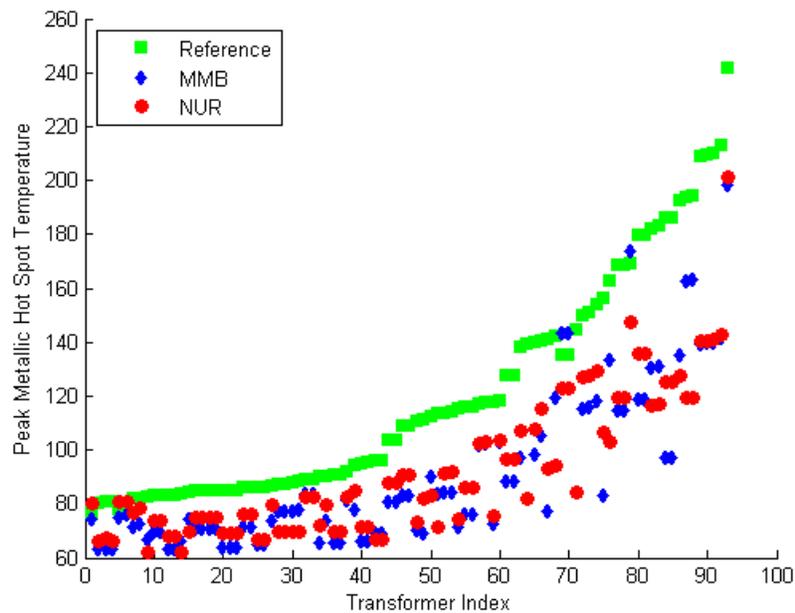

Figure I-7: Calculated Peak Metallic Hot Spot Temperature for All Transformers in a Test System with a Temperature Increase of More Than 20°C for Different GMD Events Scaled to the Same Peak Geoelectric Field
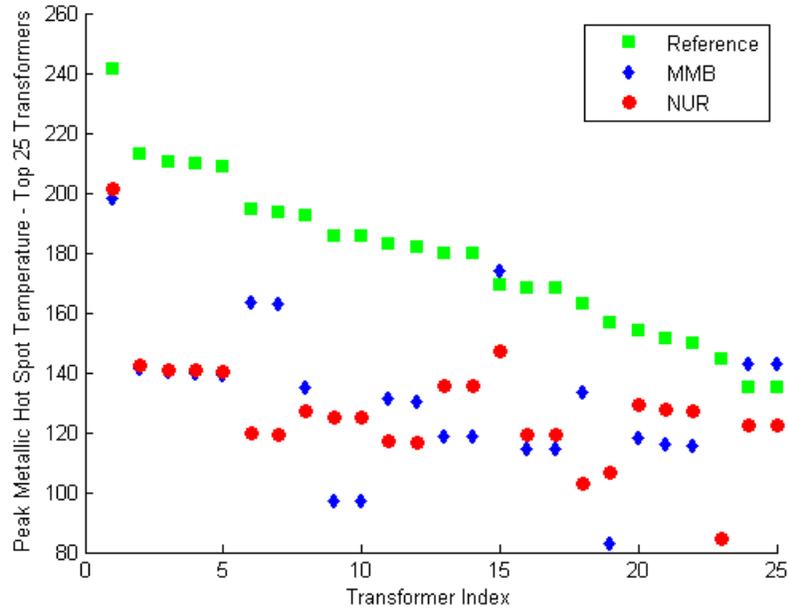
Figure I-8: Calculated Peak Metallic Hot Spot Temperature for the Top 25 Transformers in a Test System for Different GMD Events Scaled to the Same Peak Geoelectric Field
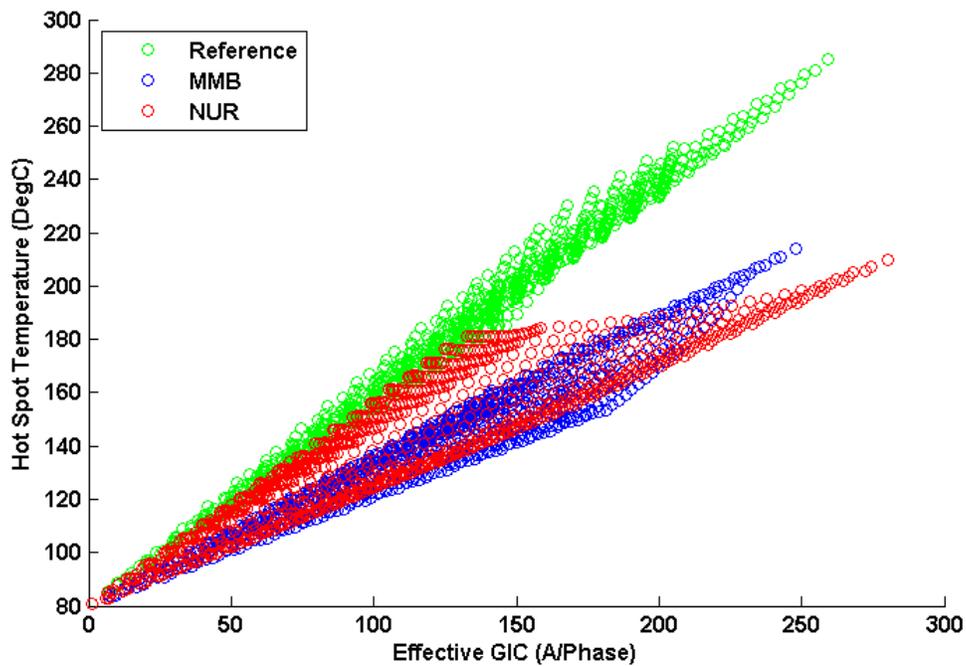

Figure I-9: Calculated Peak Metallic Hot Spot Temperature for all possible circuit orientations and effective GIC.

Appendix II – Scaling the Benchmark GMD Event

The intensity of a GMD event depends on geographical considerations such as geomagnetic latitude[6] and local earth conductivity[7] [3]. Scaling factors for geomagnetic latitude take into consideration that the intensity of a GMD event varies according to latitude-based geographical location. Scaling factors for earth conductivity take into account that the induced geoelectric field depends on earth conductivity, and that different parts of the continent have different earth conductivity and deep earth structure.

Scaling the Geomagnetic Field

The benchmark GMD event is defined for geomagnetic latitude of 60° and it must be scaled to account for regional differences based on geomagnetic latitude. To allow usage of the reference geomagnetic field waveshape in other locations, **Table II-1** summarizes the scaling factor α correlating peak geoelectric field to geomagnetic latitude as described in **Figure II-1** [3]. This scaling factor α has been obtained from a large number of global geomagnetic field observations of all major geomagnetic storms since the late 1980s [15], [24]-[25], and can be approximated with the empirical expression in (II.1)

$$\alpha = 0.001 \cdot e^{(0.115 \cdot L)} \tag{II.1}$$

where L is the geomagnetic latitude in degrees and $0.1 \le \alpha \le 1.0$.

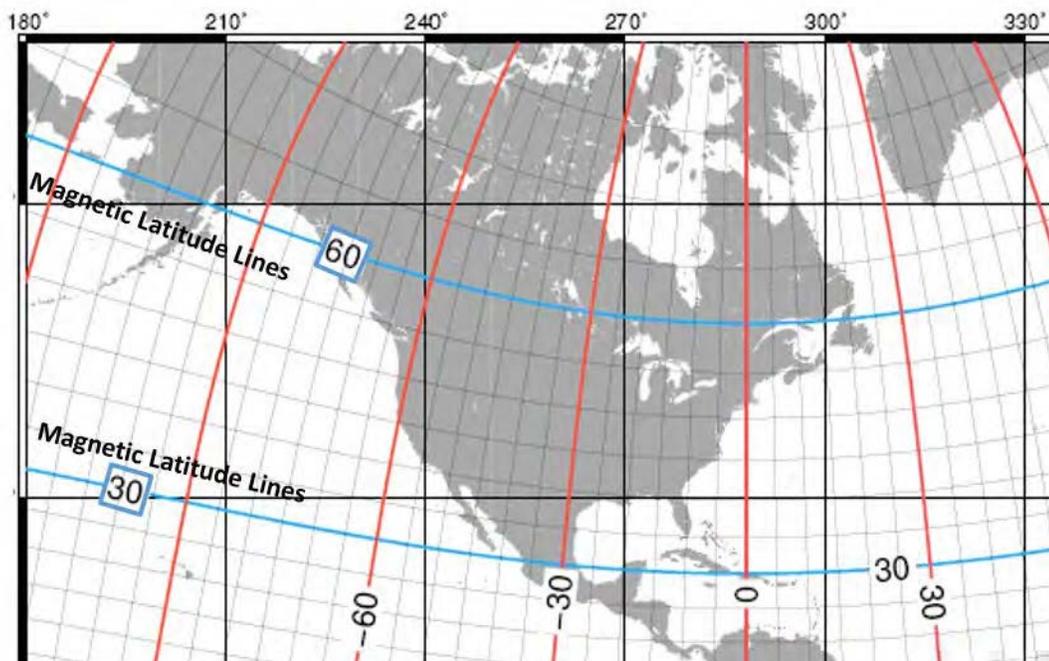**Figure II-1: Geomagnetic Latitude Lines in North America**

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[6] Geomagnetic latitude is analogous to geographic latitude, except that bearing is in relation to the magnetic poles, as opposed to the geographic poles. Geomagnetic phenomena are often best organized as a function of geomagnetic coordinates.
[7] Local earth conductivity refers to the electrical characteristics to depths of hundreds of km down to the earth's mantle. In general terms, lower ground conductivity results in higher geoelectric field amplitudes.

| Table II-1: Geomagnetic Field Scaling Factors ||
Geomagnetic Latitude (Degrees)	Scaling Factor1 (α)
≤ 40	0.10
45	0.2
50	0.3
54	0.5
56	0.6
57	0.7
58	0.8
59	0.9
≥ 60	1.0

Scaling the Geoelectric Field

The benchmark GMD event is defined for the reference Quebec earth model provided in **Table 1**. This earth model has been used in many peer-reviewed technical articles [12, 15]. The peak geoelectric field depends on the geomagnetic field waveshape and the local earth conductivity. Ideally, the peak geoelectric field, E_{peak}, is obtained by calculating the geoelectric field from the scaled geomagnetic waveshape using the plane wave method and taking the maximum value of the resulting waveforms

$$E_N = (z(t)/\mu_o) * B_E(t)$$
$$E_E = -(z(t)/\mu_o) * B_N(t) \tag{II.2}$$
$$E_{peak} = \max\left\{\left|E_E(t), E_N(t)\right|\right\}$$

where,
* denotes convolution in the time domain,
 $z(t)$ is the impulse response for the earth surface impedance calculated from the laterally uniform or 1D earth model,
$B_E(t)$, $B_N(t)$ are the scaled Eastward and Northward geomagnetic field waveshapes,
$E_E(t)$, $E_N(t)$| are the magnitudes of the calculated Eastward and Northward geoelectric field $E_E(t)$ and $E_N(t)$.

As noted previously, the response of the earth to $B(t)$ (and dB/dt) is frequency dependent. **Figure II-2** shows the magnitude of $Z(\omega)$ for the reference earth model.
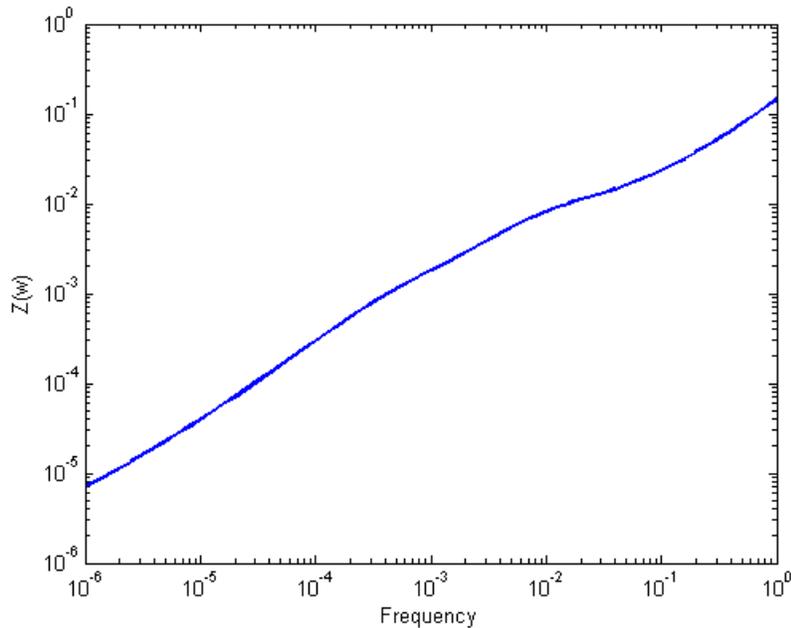
Figure II-2: Magnitude of the Earth Surface Impedance for the Reference Earth Model

If a utility does not have the capability of calculating the waveshape or time series for the geoelectric field, an earth conductivity scaling factor β can be obtained from **Table II-2**. Using α and β, the peak geoelectric field E_{peak} for a specific service territory shown in **Figure II-3** can be obtained using (II.3)

$$E_{peak} = 8 \times \alpha \times \beta \text{ (V/km)} \tag{II.3}$$

It should be noted that (II.3) is an approximation based on the following assumptions:

- The earth models used to calculate Table II-2 for the United States are from published information available on the USGS website.
- The models used to calculate Table II-2 for Canada were obtained from NRCan and reflect the average structure for large regions. When models are developed for sub-regions, there will be variance (to a greater or lesser degree) from the average model. For instance, detailed models for Ontario have been developed by NRCan and consist of seven major sub-regions.
- The conductivity scaling factor β is calculated as the quotient of the local geoelectric field peak amplitude in a physiographic region with respect to the reference peak amplitude value of 8 V/km. Both geoelectric field peaks amplitudes are calculated using the reference geomagnetic field time series. If a different geomagnetic field time series were used, the calculated scaling factors β would be different than the values in Table II-2 because the frequency content of storm maxima is, in principle, different for every storm. However, the reference time series produces generally more conservative values of β when compared to the time series of reference storm of the NERC interim report of 2012 [14], measurements at the Nurmijarvi (NUR) and Memanbetsu (MMB) geomagnetic observatories for the "Halloween event" of October 29-31, 2003, and other recordings of the March 1989 event at high latitudes (Meanook observatory, Canada). The average variation between minimum and maximum β is approximately 12 percent. **Figure II-4** illustrates the values of β calculated using the 10-second recordings for these geomagnetic field time series.
- If a utility has technically-sound earth models for its service territory and sub-regions thereof, then the use of such earth models is preferable to estimate E_{peak}.

- When a ground conductivity model is not available the planning entity should use the largest β factor of adjacent physiographic regions or a technically-justified value.

Physiographic Regions of the Continental United States
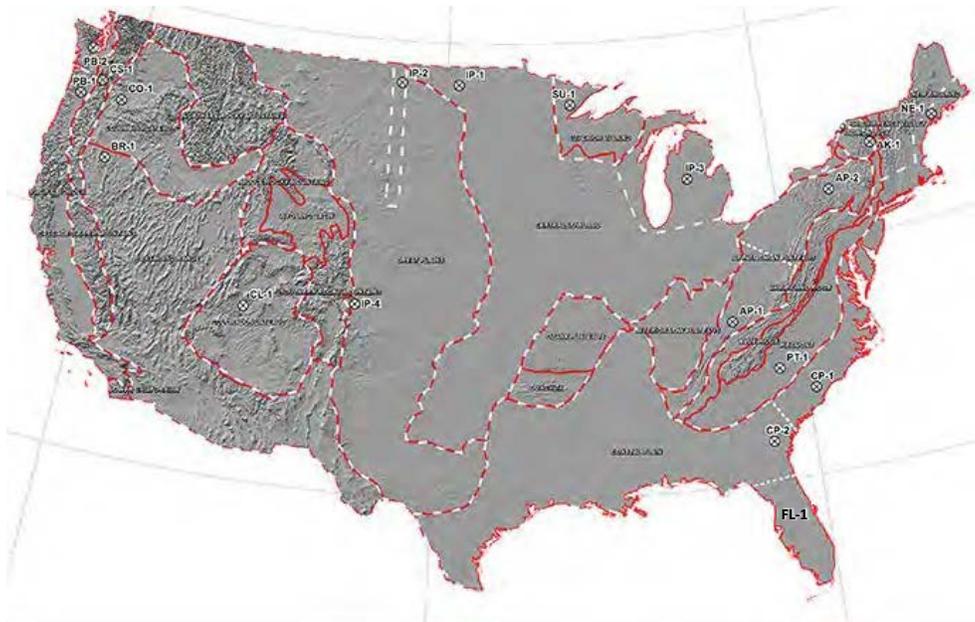
Physiographic Regions of Canada

Figure II-3: Physiographic Regions of North America

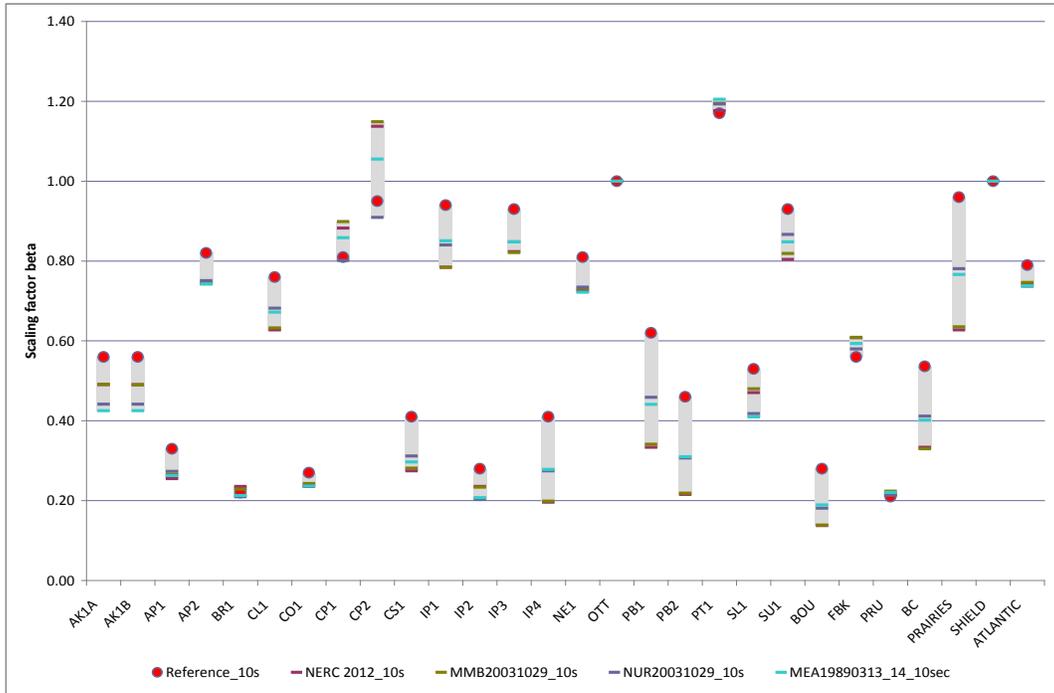| Table II-2 Geoelectric Field Scaling Factors	
USGS Earth model	Scaling Factor (β)
AK1A	0.56
AK1B	0.56
AP1	0.33
AP2	0.82
BR1	0.22
CL1	0.76
CO1	0.27
CP1	0.81
CP2	0.95
FL1	0.74
CS1	0.41
IP1	0.94
IP2	0.28
IP3	0.93
IP4	0.41
NE1	0.81
PB1	0.62
PB2	0.46
PT1	1.17
SL1	0.53
SU1	0.93
BOU	0.28
FBK	0.56
PRU	0.21
BC	0.67
PRAIRIES	0.96
SHIELD	1.0
ATLANTIC	0.79

Figure II-4: Beta factors Calculated for Different GMD Events
Red circles correspond to the values in Table II-2

Example Calculations

Example 1
Consider a transmission service territory that lies in a geographical latitude of 45.5°, which translates to a geomagnetic latitude of 55°. The scaling factor α calculated using II.1 is 0.56; therefore, the benchmark waveshape and the peak geoelectric field will be scaled accordingly. If the service territory has the same earth conductivity as the benchmark then β=1, and the peak geoelectric field will be

$$\alpha = 0.56$$
$$\beta = 1.0$$
$$E_{peak} = 8 \times 0.56 \times 1 = 4.5V/km$$

If the service territory spans more than one physiographic region (i.e. several locations within the service territory have a different earth model) then the largest α can be used across the entire service territory for conservative results. Alternatively, the network can be split into multiple subnetworks, and the corresponding geoelectric field amplitude can be applied to each subnetwork.

Example 2
Consider a service territory that lies in a geographical latitude of 45.5° which translates to a geomagnetic latitude of 55°. The scaling factor α calculated using II.1 is 0.56; therefore, the benchmark waveshape and the peak geoelectric field will be scaled accordingly.

The service territory has lower conductivity than the reference benchmark conductivity, therefore, according to the conductivity factor β from Table II-2., the calculation follows:

Conductivity factor β=1.17

$$\alpha = 0.56$$

$$E_{peak} = 8 \times 0.56 \times 1.17 = 5.2V / km$$

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