Protecting America's Electric Grid Against Solar Geomagnetic Disturbances

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Executive Summary

The North American electric transmission system is becoming increasingly susceptible to permanent equipment damage, both prompt and delayed damage from solar geomagnetic disturbances (GMDs). Unlike man-made electromagnetic pulse attacks that might be deterred by active and passive defenses and threat of retaliation, the sun is undeterrable.

Recent studies of the likelihood of a severe solar geomagnetic storm place the risk of a storm capable of permanent damage to the northern hemisphere electric power grids at about 10 percent per decade; with a lesser risk of severe damage to electric grids in the Northern Hemisphere of about 4 to 6 percent per decade.[1]

An assessment in 2013 by Lloyds of London, with research by Atmospheric and Environmental Research of Lexington, Massachusetts, forecast that a Carrington-level (1859) extreme geomagnetic storm impacting the United States "is almost inevitable" with a return period of 50 years for a less severe Hydro-Quebec solar storm (March 1989) and 150for a Carrington Event.[2] Lloyds forecast 20 to 40 million people to be at risk of extended blackouts lasting between 16 days and one to two years, with total economic losses up to $2.6 trillion dollars.[3] This assessment placed the greatest risk of severe electric grid outages along the Atlantic corridor between New York and Washington, D.C., with regions of the Midwest in states such as Michigan and Wisconsin, and regions along the Gulf Coast at elevated risk. Subsequent modeling indicates that the state of Minnesota and perhaps states along the New England coast are also at elevated risk of cascading blackouts from solar storms.[4]

The good news is that equipment to protect against EMP's ultra-fast (E1) voltage surges and later long-line (E3) voltage surges can also protect high voltage transformers and generator equipment that is at risk from naturally occurring solar storms. So if there are both a national policy and cost-recovery mechanisms to protect against high altitude EMP (HEMP), these hardware protections can also protect against GMD hazards to the same grid equipment. The

[1] Mary Lasky, et al. Powering Through: From Fragile Infrastructures to Community Resilience, EMP SIG of InfraGard, December 2016, p. 3, citing multiple sources in Footnote 9.
[2] It is worth noting that the Earth nearly missed a Carrington-class event in 2012 due to a nine day separation between a major solar storm's charged particle flux arrival and our planet's orbital movement into a position of danger.
[3] Lloyds, and Atmospheric and Environmental Research, Solar Storm Risk to the North American Electric Grid, InfraGard EMP SIG, June 2013, p. 4. Available at: https://www.lloyds.com/~/media/lloyds/reports/emerging%20risk%20reports/solar%20storm%20risk%20to%20the%20north%20american%20electric%20grid.pdf .
[4] Studies by J. J. Love and Adam Schultz presented at the Geomagnetic Disturbance Task Force of NERC, Charlotte, N.C. on February 22, 2017, indicate, from 3D magnetotelluric modeling, potential voltage surges inland of water-land boundaries, as well as edges of the Columbia plateau in Oregon and the Colorado plateau in the Southwest. Magnetotelluric surveys of the New England states will be completed this summer. The Love and Schultz studies are available on the NERC GMD Task Force website at http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx .

converse is not true: protecting only grid equipment connected to long electric lines or at end-of-line locations from quasi-DC currents will not protect against E1 voltage spikes, which place at risk a broader class of control and communications equipment.

Furthermore, the North American electric utilities opted neither to collect historical solar storm effects data (before May 2013) for North America nor to validate the so-called NERC GMD Benchmark Model[5] using empirical data from the North American grid. NERC would only confirm that only one high voltage transformer had been destroyed during or immediately after a severe solar storm. Resilient Societies has now confirmed at least nine other large power transformers have exploded or been destroyed during GMD events of the past three decades. Once again, the higher protection requirements for high altitude EMP can protect against more extensive transformer fleet losses than NERC modeled for severe solar storms.

The NERC-FERC (GMD-only) standard now in force for assessment of hardware protective equipment is so low (no recognized hazard below 75 amps per phase of transformer current; no augmented risk for coastal zones, etc.) that almost no electric utilities in the United States and few in Canada will be required to purchase neutral ground blockers or series capacitors, or other equipment that can protect high voltage transformers and autotransformers from severe solar storms.

The solar storm standard is also a barrier to EMP protection.[6] To begin with, the standard ignores the high-amplitude, E1 fast pulse effects from a high-altitude nuclear burst. Also, where GMD effects levels trend down at southerly grid locations, the slow pulse E3 levels from a high altitude nuclear burst increase. Thus, utilities at lower latitudes that require no protection against GMD under the NERC standard are more susceptible to E3. Utilities, having exerted a multi-year effort to limit protection requirements for GMD are likely to resist repeating the same difficult process to upgrade their protection to include EMP requirements.

Of roughly 2,000 to 2,500 extra high voltage transformers vulnerable to damage, explosion or total loss in a severe solar storm, only one transformer in Wisconsin is known to now operate with GMD-protective equipment. This equipment has successfully protected a large power transformer since March 2013. The rest of the bulk power system remains at risk of equipment losses that could trigger cascading and long-term grid outages.

Because the scientifically-unvalidated NERC-FERC standard for GMD hardware protection became final on January 19, 2017, and because neither Resilient Societies nor three other

[5] See the NERC GMD Task Force website for the year 2014 NERC publication of the GMD benchmark model, approved by FERC in Order No. 830, September 22, 2016.

[6] In 2013 FERC also adopted unrealistic and unworkable standards for "operating procedures" upon warning of an impending solar storm. This NERC Standard EOP-010-1 excluded entirely generator operators with the most critical equipment to protect. Further, during severe solar storms, transmission operators may find that circuit opening and closing is unworkable as some owners experienced in March 1989. Temporary disruption of communications and loss of system visibility are also risks to operational mitigation efforts of transmission operators.

groups challenged FERC Order 830 in a Federal Court of Appeals by March 20th, the FERC solar storm standard is now unappealable.

What can be done to protect the North American electric grid?

Because the E3 hazard levels from a HEMP attack are substantially higher than projected for solar storms, the adoption of an "all hazards" standard for EMP, Intentional Electro Magnetic Interference (IEMI), and GMD protection can mitigate combined EMP & GMD hazards to critical grid equipment. This can be achieved through an Executive Order of the President or through federal legislation that might have the additional benefit of providing "safe harbor" liability protection for grid owner investments that meet technical standards for EMP protection.[7]

Options to develop "all hazards" protection for the electric grid, now before the Congressionally-mandated EMP Commission, have the potential to rescue critical infrastructure protection from the regulatory morass of the past five years.

For Three Classes of Solar Storm Hazards, NERC & FERC Model Only One

Three classes of solar storm should be included in modeling and "Corrective Action Plans" of North American electric utilities. These three classes are:

- **Coronal mass ejections (CMEs)** that, when reaching planet Earth distort the Earth's geomagnetic fields, inducing electric fields at the Earth's surface that cause geomagnetic induced currents (GICs) to flow in long-line grid transmission systems and equipment. These GICs tend to have greater intensity at higher latitudes, except that the most severe CME events tend to peak at more southerly, mid-continental latitudes;
- **Coronal hole (CH)** magnetic ropewalk twisted pair streams, that emerge from lower density plasmas and that, especially in the declining phase of the solar geomagnetic half cycle, stream via solar winds nearly continuous but oscillating magnetic waves, with lower energy output but usually with higher wind speeds than CMEs, resulting in geomagnetic fields that can persist for days or weeks and cause overheating, damage and destruction to high voltage transformers (They caused fires in at least two Midwestern nuclear generators); and
- **Storm Sudden Commencement (SSC) or sudden reversing magnetic storms.** These storms occur at any latitude, generally without benefit of advance warning from the Space Weather Prediction Center (SWPC). Twelve high voltage transformers in South Africa during the October 2003 Halloween (CME) storm are examples. For example, on November 9-10, 1998, the sudden reversal of a north-to-south solar-induced electrojet

[7] FERC does not presently have the legal authority to provide liability limits for electric utilities that meet FERC reliability standards, except for immunity from FERC fines. See FERC Order No. 830, paras. 121 and 122 (September 22, 2016). If the executive branch establishes technical conditions for eligibility, the Congress could provide tax credits and/or limits on liability, hence a "safe harbor" from EMP-IEMI-GMD financial hazards for grid protection program participants.

with a south-to-north electrojet caused vibrations in a Seabrook, N.H. Phase A generator step up transformer which loosened a stainless steel bolt, and melted the low voltage windings.

Resilient Societies requested that NERC collect case histories of transformer fires, damage or explosions concurrent or immediately after solar storms in 2011, with start-up of the Geomagnetic Disturbance (GMD) Task Force. NERC declined, and was content to have public awareness of just one extra high voltage transformer with melted windings during a solar storm. This was the Salem 1 nuclear plant's 500 kV Generator Step Up transformer on a coastal salt marsh in Lower Alloways Creek, New Jersey, adjacent to Delaware Bay. Metatech, a California research corporation identified at least four other transformer fires or explosions in the service territory of Commonwealth Edison during a three week period in 1994 (March 23 through April 15).[8]

At times, a coronal mass ejection will be paired with a coronal hole proton stream without visible ejecta. This concurrence of CMEs and coronal hole (CH) proton streams hitting the same regions of planet Earth complicates modeling of solar storm hazards to bulk electric systems. Because CH impacts can last for days or weeks or months, cumulative damage to high voltage transformers may occur. An outstanding technical issue concerns whether the transformers are more susceptible to damage when they are further stressed by a short-acting but more powerful CME. Some of the rapidly developing space science literature models twisted pairs of magnetic energy that escapes the sun. When the twisting is left-handed, some space science studies suggest there is more likely geomagnetic impact on the Northern Hemisphere of the Earth.

The science of "coronal whole" modeling has advanced with the launch of Skylab in 1973-1974; improved with soft X-ray imaging by the Japanese YOHKOH space satellite in the late 1970s; and much advanced in the era of the ACE and DSCOVR satellites in orbit since year 1997. Credit should be given to an Interagency Space Weather Operations, Research and Mitigation Task Force implementing President Obama's Executive Order 13744, "Coordinating Efforts to Prepare the Nation for Space Weather Events."[9]

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[8] See John A. Kappenman, Geomagnetic Storms and Their Impacts on the U.S. Power Grid, Goleta, CA: Metatech Corporation, January 2010, Meta-R-319, p. 101. Significant follow-on research has been conducted by the CEO of Metatech, Dr. William A. Radasky on "coronal hole" hazards to electric grids.

[9] Section 5 of E.O. 13744 issued October 13, 2016, instructs the Secretary of Energy, in consultation with the Secretary of Homeland Security, to develop "a pilot program" to test and evaluate "devices that mitigate the effects of geomagnetic disturbances on the electrical power grid" with *in situ* equipment. The Executive Order is available at: https://www.federalregister.gov/documents/2016/10/18/2016-25290/coordinating-efforts-to-prepare-the-nation-for-space-weather-events .

Charting a Prudent Course for Grid Protection Despite Modeling Failures

How should prospective space science development affect national security policies to protect critical infrastructures, especially the electric grid?

First, we need to recognize that the more energetic coronal mass ejections will determine a minimum sizing and ruggedness of grid protective equipment, series capacitors, overvoltage protectors, etc. However, continuous streams of CH solar winds, though lower in amplitude, can, in themselves, cause dangerous, cumulative thermal effects and may exacerbate the effects of CMEs. The coronal hole winds are generally faster than most CME wind speeds, often exceeding 700 km per second. However, the July 22-23, 2012 coronal mass ejection, which planet Earth avoided, had far higher wind speeds, but often solar hole wind streams can catch up and enhance CMEs already affecting Earth. It appears that the solar geomagnetic threat should be the maximum CME hazard expected, at times exacerbated by compression and intensification of the geomagnetic field by overtaking coronal hole magnetic winds.[10]

Second, we should not underestimate cumulative damage hazards to the North American electric grid by *only* assessing damage from coronal mass ejections. At least five of ten large power transformers (including an autotransformer) have caught fire or exploded during relatively extended time periods within which lower energy coronal hole wind streams have impacted planet Earth. With assistance from Commission librarians, we have retrieved the microfilm "licensee event reports" (LERs) from the legacy archives of the Nuclear Regulatory Commission. Although the owner of four transformers destroyed during a multi-week coronal hole period of geomagnetic streaming (Commonwealth Edison, March 23 - April 15, 1994) postponed the installation of a replacement transformer due to space weather warnings on April 15, 1994, that owner-operator, Commonwealth Edison, did not promptly notify the Nuclear Regulatory Commission that the cause of the transformer fires and explosions was a coronal hole solar storm. Because another high voltage transformer exploded the evening of April 15th (during the period of warned space weather hazard), ComEd deliberately deferred installation of a replacement GSU transformer.[11]

There is persistent under-reporting of solar storm impacts on long replacement-time grid equipment – even for nuclear licensees, for which it is a felony to misreport or fail to report a report-triggering event. Concurrent with two of the transformer fires at nuclear power plants during the coronal hole "spring" of 1994, two generators also experienced generator hall fires

[10] We note that the E3 portion of the nuclear EMP waveform magnitude outstrips even the Carrington event so protection against the largest known GMD levels will likely be ineffective against high altitude nuclear burst effects.

[11] A Commonwealth Edison engineer did contact John A. Kappenman (then employed at Metatech) and obtained GIC readings from Minnesota, Indiana, and Ohio, which enabled extrapolation of the approximate geoelectric fields in the Commonwealth Edison electric service region. (Personal Communication, W. R. Harris with John A. Kappenman, March 30, 2017.)

at the same utility facilities and on the same nights as the Generator Step Up transformers caught fire. Again, licensee event reports failed to note that the generator fires occurred during coronal hole streaming towards Earth.

Tentatively, it appears that all but two of ten transformer losses we have identified as occurring during solar storms occurred in a "coastal" location: adjacent to the Atlantic Ocean, or proximate to lower Lake Michigan. Did NERC attempt to model a "coastal effect" in the Benchmark Model that FERC has now approved? Even after our requests? It did not.[12]

Still under review are transformer fires at nuclear power plants at Diablo Canyon, California and Indian Point, New York, where generator step up transformers caught fire during periods of earth impact from streaming solar coronal holes (CHs). Diablo Canyon is adjacent to the Pacific Ocean, and Indian Point is adjacent to the Hudson River. We have potential identification of another two coastal sites where transformers failed at nuclear power plants during solar storms.

How many transformer fires at other than nuclear power plants coincided with coronal hole geomagnetic streams impacting planet Earth or more visible coronal mass ejection solar storms? We have almost no reliable publicly-available reporting, because owner-operators of fossil fuel and renewable generating facilities have no duty to report losses of transformers or generators during solar storms, except for periods in or after May 2013.

There was one transformer fire at a coal generating power plant in the Chicago area during the coronal hole streaming events of spring 1994, but generally, utilities fail to report to the federal government any coincidence of transformer losses at fossil fuel generating facilities during geomagnetic disturbance events impacting planet Earth.[13]

Since we have near-zero confidence in the NERC-FERC modeling of solar storm hazards to the electric grid, what should national leaders do to protect critical infrastructures?

For only modest cost-increases to design and manufacture more robust neutral ground blocking equipment to protect against the larger pulses and quasi-DC currents from man-made EMP rather than the lesser naturally occurring GMD, and to protect vulnerable elements of generators and control systems, the prudent course of action is to develop, simulate, verify, and promulgate protection standards for man-made EMP protection, including both E1 and E3

[12] In FERC Order No. 830, that Commission did require that NERC "further analyze earth conductivity models … and the GMD research work plan should specifically investigate "coastal effects" on ground conductivity models." FERC Order 830, ¶ 78, 156 FERC ¶ 61,215, Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events," TPL-007-1.

[13] The Electric Power Research Institute (EPRI) manages a so-called SUNBURST database providing GIC reports for project member sites; but not unexpectedly, this historic database has not been released to public researchers. Of special interest would be the GIC monitoring data from the period of "coronal hole" coincidence with transformer and generator equipment losses in March-April 1994. It is our understanding that SUNBURST data for year 1994, among other years, was lost to the SUNBURST program because of computer backup failure(s).

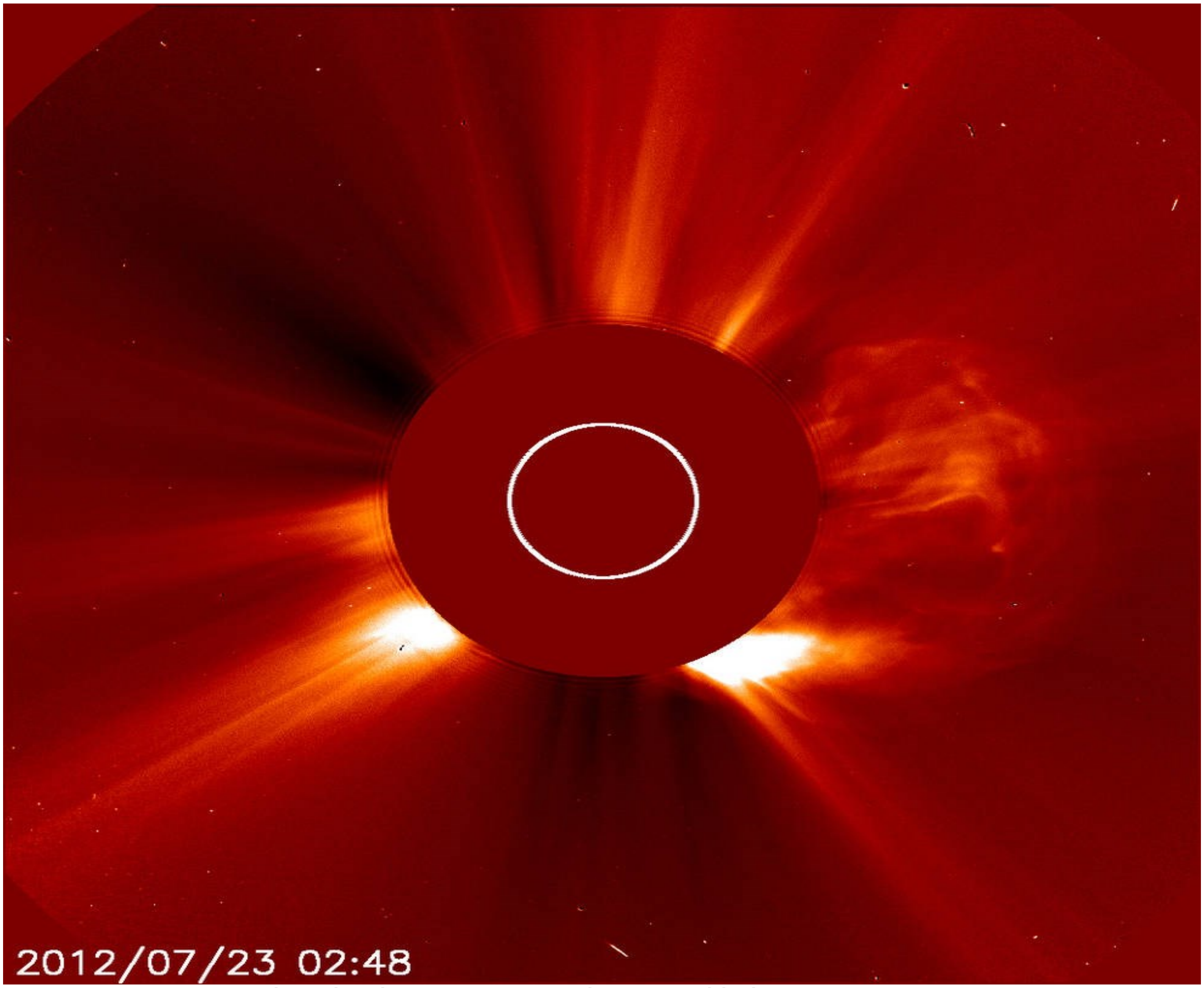
protections. Then FERC should authorize a "best practices" program with allowable cost recovery so electric utilities can purchase equipment with robust protective capabilities against HEMP, IEMI, and GMD hazards – an "all hazards" strategy that will save money compared to three separate programs.

If instead, the United States commits to a separate, stove pipe solar storm protection standard based on the modeling by NERC and its registered utility entities, we anticipate false reassurances and virtually no practical protection of our electric grid: whether from solar storms or man-made EMP weapons.

Two final sections of this report section provide illustrative images and Foundation regulatory filing highlights.

Images

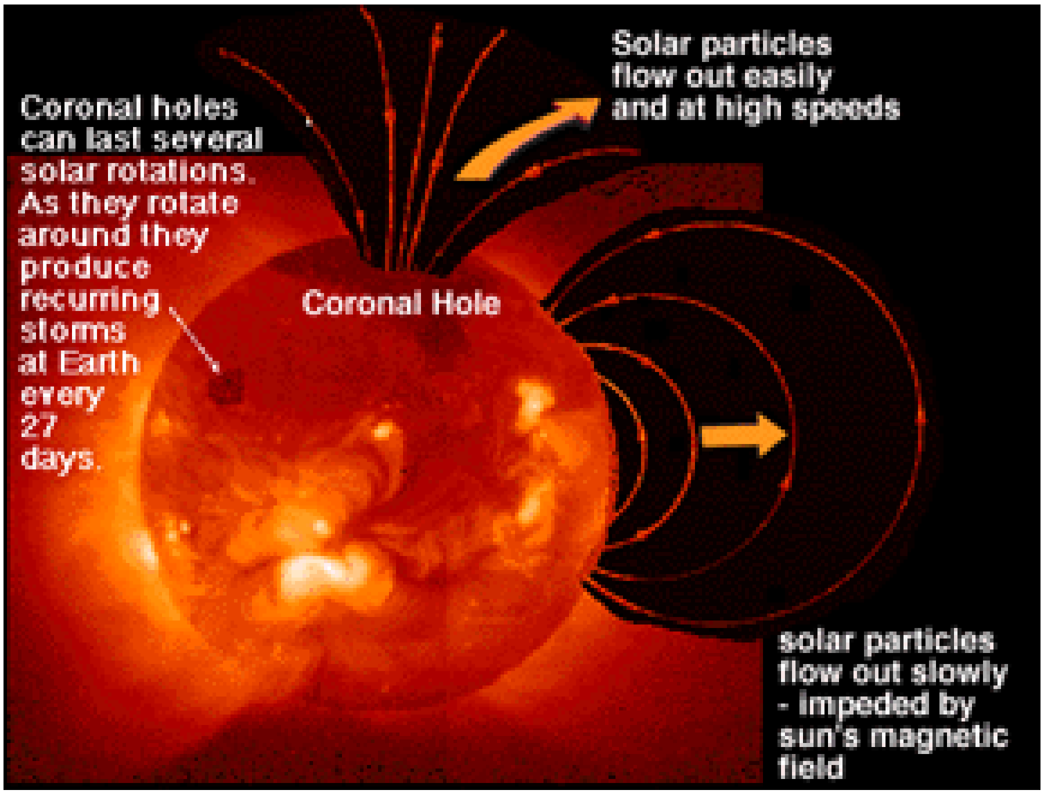
Images include a large coronal mass ejection (CME) event; a soft X-ray image of the sun during a period of coronal hole streaming; and a picture of a damaged generator step-up transformer (at Seabrook Station, New Hampshire) during a sudden storm commencement (SSC) or sudden electrojet reversal.



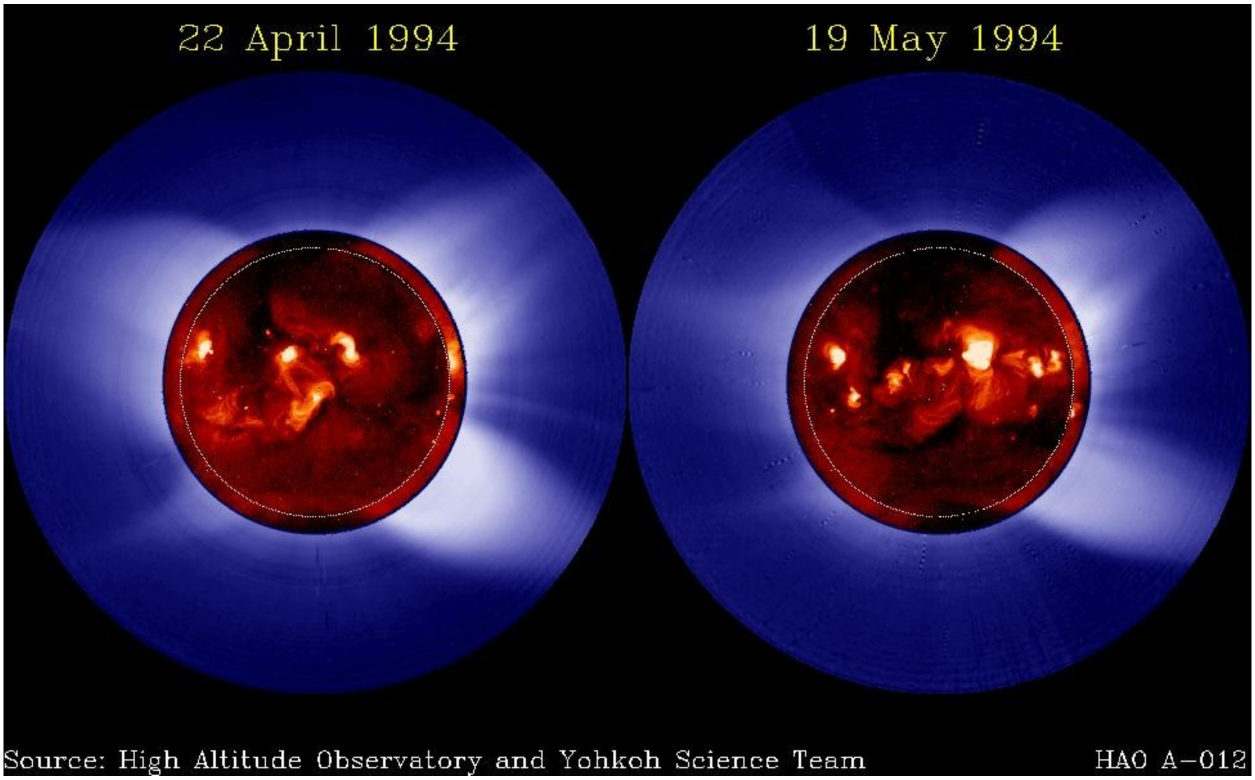
This image was captured by ESA/NASA's Solar and Heliospheric Observatory (SOHO) on July 22, 2012 at 10:48 PM EDT. On the right side, a cloud of solar material ejects from the sun in one of the fastest coronal mass ejections (CMEs) ever measured.
Credits: ESA&NASA/SOHO

An unusually energetic coronal mass ejection (CME)
July 22-23, 2012

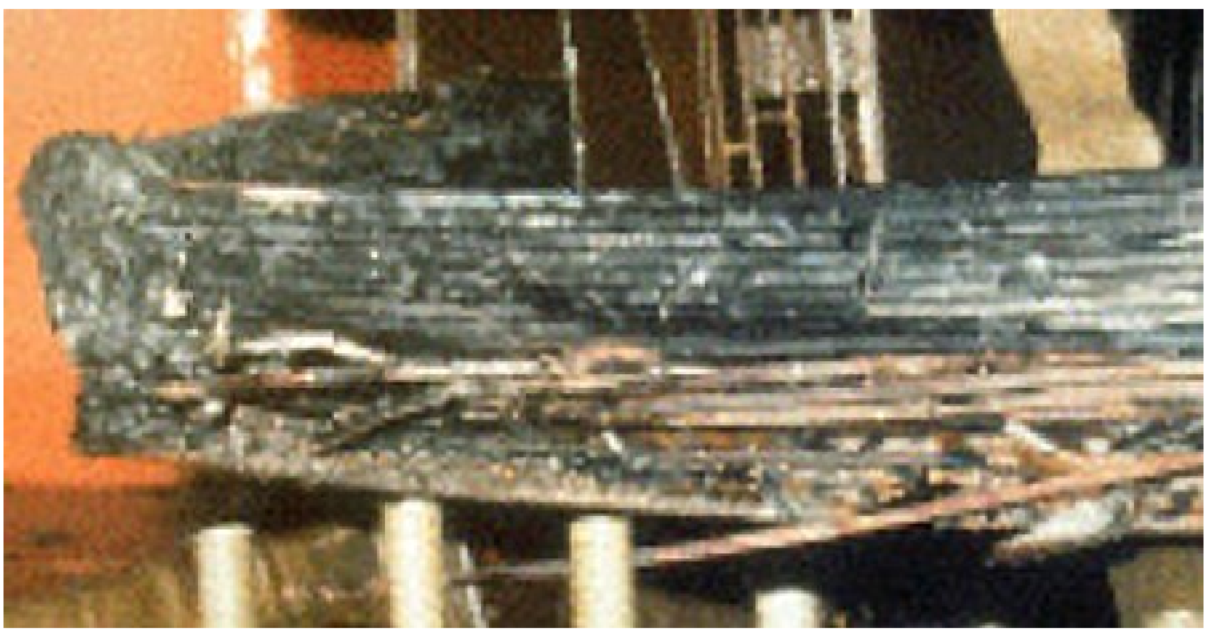
Due to the rotation of the sun every 27 days, this coronal mass ejection, though substantially in the plane of earth’s orbit, was not a direct threat to critical infrastructures on planet Earth. Since this extreme event occurred during the relatively modest Solar Cycle 24, this event “demonstrates that extreme space weather conditions such as those during March of 1989 or September 1859 can happen even during a modest solar activity cycle….” For further analysis, see D. N. Baker, et al., “A major solar eruptive event in July 2012: Defining extreme space weather scenarios,” Space Weather v. 11 (Oct. 2013), pp. 585-591. See full article at: http://onlinelibrary.wiley.com/doi/10.1002/swe.20097/full .



A solar coronal hole with reduced plasma density facilitates the escape of protons that coalesce into magnetic ropewalk structures, and some of these stream towards planet earth with high speed coronal winds, many lasting for days or weeks.



Coronal hole images 22 April and 19 May 1994 provide images from a period of coronal holes active proximate to the three-week period with four transformer losses in the Midwest during repeated nightly solar wind streaming, 23 March - 15 April 1994.



Melted low voltage winding at 345 kV GSU transformer, Seabrook Station, NH, during mild solar storm with reversal of electrojets, transformer saturation, vibration of stainless steel bolt, damage to Phase A transformer, Nov. 10, 1998, 12.2 day outage.

Regulatory Highlights -
Resilient Societies Initiatives for Solar Storm Mitigation

The phrase “regulatory highlights” may be an oxymoron. The Foundation for Resilient Societies has had significant influence on the electric power reliability regulatory and legal priorities. Some of the more highly visible and influential Resilient Societies’ initiatives to protect against solar storms follow.

Before FERC Order No. 779 (May 2013), Resilient Societies urged FERC to adopt a combined mitigation standard for High Altitude EMP (HEMP) and GMD together.

In FERC Order 779, adopted in May 2013, the Commission refused to order a combined standard. This “silo solution” strengthened incentives for NERC and its Standard Drafting Team to exclude elements of solar storm hazards that might increase the threat levels:

- consideration of all three classes of solar storms, not just CMEs;
- modeling of a “coastal effect” or more generally a Dirichlet boundary condition;
- non-exclusion of all transformers, generators, and other long replacement-time equipment damaged or destroyed during past solar storms;
- model vibration effects on transformer losses;
- assess insurance data claims that confirm no statistically significant reduction of electric equipment claims at lower latitudes;
- third-party-verified testing to destruction of critical grid equipment to determine equipment voltage/current failure thresholds.

In April 2015 we publicly filed indicators of widespread deployment of GMD induced current (GIC) monitors, and asked that GIC threshold alarms or near-real-time data be reported to the DOE Operations Center. Although FERC never mandated installation of GIC monitors or mandatory reporting to a DOE Operations Center, in December 2015 the Congress enacted the FAST Act. This new law added Section 215A to the Federal Power Act. As a consequence, with presidential designation, the Secretary of Energy can mandate energy emergency programs, electric connections, disconnections or interconnections, and grant cost recovery for sequential 15-day emergency periods.

Also in April 2015 we asked the Office of Science and Technology Policy (OSTP) in the Executive Office of the President to develop more comprehensive infrastructure protection programs, rather than emphasize space weather forecasting improvements he Draft National Space Weather Action Plan of May 2015 reflected some of these additional priorities.

In June 2015 we took NERC’s First Level II standards appeal in a decade of standards development to a subcommittee of the NERC Board of Trustees. This was the transmission planning standard TPL-007-1.

The NERC Board declined our appeal, refused to address the substantive failings, and just found their procedures were adequate. With a webcast hearing and a transcript in NERC's permanent records, we did signal that a failure to apply scientific methods would not remain unnoticed.

On July 27, 2015, with corrective additions on August 11th, we filed with FERC a comprehensive critique of what we considered to be a pervasively defective standard to assess mandatory hardware protection during solar storms. This was FERC Docket RM15-11-000. At the request of the FERC Chairman, we did outreach to U.S. and international science experts to file on experience with grid critical equipment in past solar storms. Though successful in our outreach, we were generally unsuccessful in separating the FERC Commissioners from NERC's weak standard and unvalidated NERC modeling. Except for FERC's addition of a "coastal effect" for potential future modeling, elimination of a threat lowering "hotspot averaging concept," and potential release of some geomagnetic data, we failed to attain our goal: a remand of the defective solar storm standard back to NERC.

Weakness in what became FERC Order 830 (solar storm assessments and potential corrective action plans), which we shared with a Save the Grid Coalition, did precede the successful reconstitution of the Congressional EMP Commission signed by President Obama on November 25, 2015.[14] That law mandated concurrent assessment of man-made electromagnetic pulse (EMP) threats, intentional electromagnetic interference (IEMI) devices, and naturally occurring geomagnetic disturbances in the context of combined arms hostilities.

So our less-than-successful efforts before FERC to institute "all hazards" threat mitigation became the canary in the coal mine preceding Congressional reconstitution of the EMP Commission.

As for the EMP Commission, though it was established in November 2015, President Obama's Department of Defense did not advance the administrative contracting through December 2016. So the first meeting of the revived EMP Commission only took place in the last full week of January 2017, costing more than one year in lost opportunities for Commission research and deliberation. While the life of that Commission may be extended, from a technical perspective, the legal authority of the EMP Commission will expire on June 30, 2017.

In contrast, the Foundation for Resilient Societies exercises no governmental powers, but its mission does not expire by the terms of any Act of Congress.

[14] Section 1089 of the National Defense Authorization Act for FY2016, November 25, 2015.

Background on the Foundation Resilient Societies

The Foundation for Resilient Societies is a non-profit dedicated to cost-effective protection of critical infrastructures from infrequently occurring natural and man-made disasters. Resilient Societies is the only non-profit that consistently participates in FERC rulemakings for grid security standards. We have taken the lead in preparing cost estimates for EMP protection, an essential precondition for state and federal legislation. Our staff overlaps with the Congressional EMP Commission. For more information, see our website at www.resilientsocieties.org.