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OVERVIEW OF SOLAR GEOMAGNETIC DISTURBANCES

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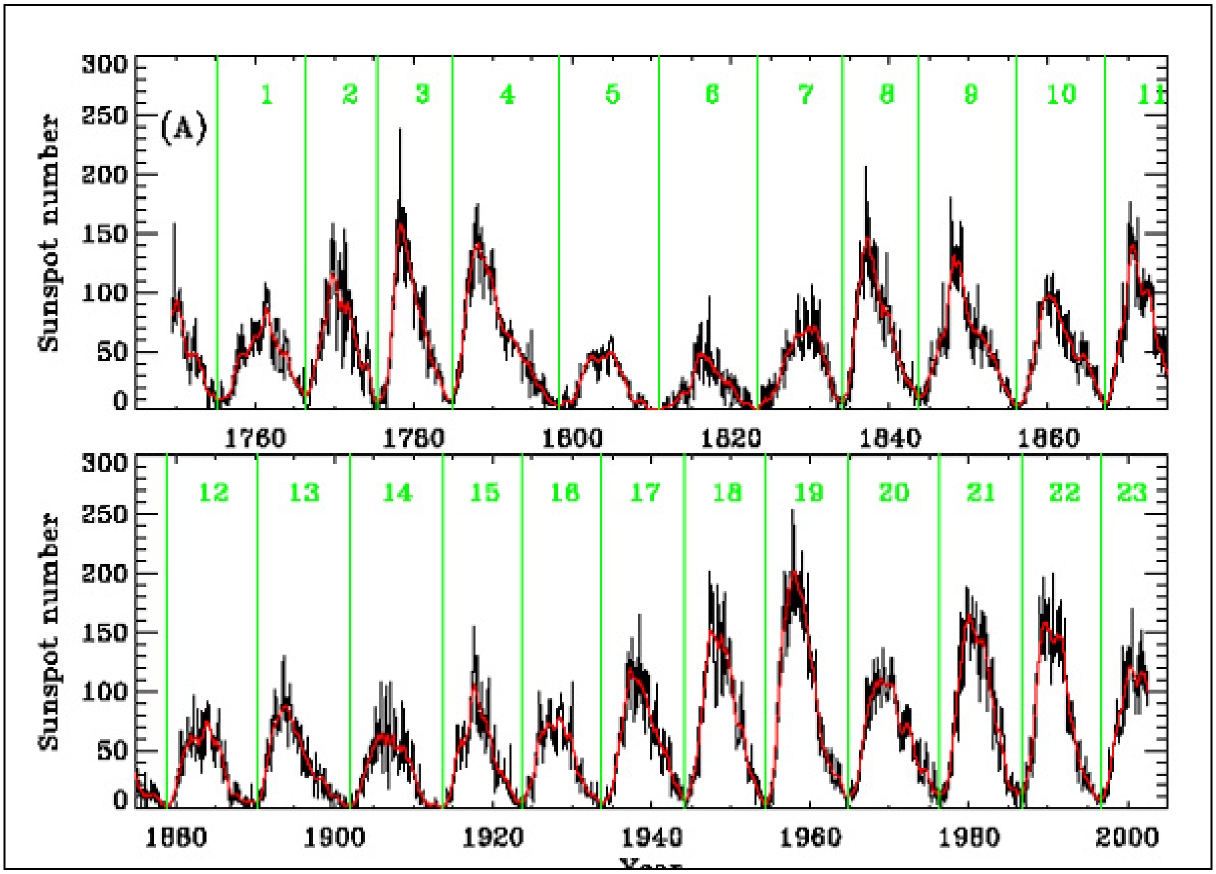
BACKGROUND

Sunspots are bursts of intense electromagnetic radiation, 1,000 to 10,000 times more intense than Earth's magnetic field. Variations in solar magnetic activity since 1745 indicate that the number of sunspots fluctuates cyclically, according to an 11-year irregular solar magnetic cycle (see Figure 1). During periods of maximum solar magnetic activity, sunspots are more frequent than average. Researchers have noted that the 11-year solar magnetic cycle matches the cycle of geomagnetic activity (i.e., magnetic activity on Earth).[1]

Figure 1 – Variations in the Number of Sunspots since 1745



Source: Canadian Space Agency.

Solar magnetic fields that are too large to be contained locally often erupt to the surface of the sun with a large interior mass of solar particles. These particles will either emit intense electromagnetic radiation (known as solar flares), or take off into space as coronal mass ejections (CMEs).[2]

Solar flares are electromagnetic radiation travelling at the speed of light (i.e., like sunlight, they can reach Earth in approximately 8.5 minutes). They typically affect Earth by heating and swelling the atmosphere, and can possibly change the chemistry of the middle atmosphere.[3]

1 Canadian Space Agency, *Sunspots: A Brief History*, http://www.asc-csa.gc.ca/eng/sciences/sunspots2.asp.

2 Canadian Space Agency, *Solar Storms*, http://www.asc-csa.gc.ca/eng/sciences/solar_storms.asp.

3 Ibid.

CMEs, on the other hand, are "billion-ton clouds of solar plasma" that may take one to several days to reach Earth. When they first leave the sun, they are bright and easy to see. However, as they expand into space their visibility is quickly reduced, leading them to appear "a billion times fainter than the surface of the full Moon" as they reach the orbit of Venus, and virtually transparent by the time they reach Earth.[4] CMEs can shake Earth's magnetic field, inducing geomagnetically induced currents (GICs) from the upper atmosphere to the ground. If a GIC is powerful enough, it could "overload circuits, trip breakers, and in extreme cases melt the windings of heaving-duty transformers."[5]

CMEs can also affect airplanes flying over Earth's polar regions, where space radiation can trigger "radio blackouts, navigation errors and computer reboots."[6] To avoid the poles during a solar geomagnetic storm, some flights would have to take longer routes, which could increase the time, money and fuel required to operate these flights.[7]

EXAMPLES OF MAJOR GEOMAGNATIC DISTRUBANCES

According to the U.S. National Aeronautics and Space Administration (NASA), "[every] hundred years or so, a solar storm comes along so potent it fills the skies of Earth with blood-red auroras, makes compass needles point in the wrong direction, and sends electric currents coursing through the planet's topsoil."[8] The most famous solar storm is the 1859 Carrington Event, which "shocked telegraph operators and set some of their offices on fire."[9] According to the National Research Council, between 28 August and 4 September 1859, "auroral displays of extraordinary brilliance were observed throughout North and South America, Europe, Asia, and Australia, and were seen as far south as Hawaii, the Caribbean, and Central America in the Northern Hemisphere and in the Southern Hemisphere as far north as Santiago, Chile."[10]

On 13 March 1989, a less severe solar storm knocked out power across Quebec for over nine hours.[11] "The large solar magnetic impulse caused a voltage depression […] that could not be mitigated by automatic voltage compensation equipment," according to the National Research Council.[12] Furthermore, the storm's rapid impacts on Hydro-Québec's grid did not give the system operators

4 National Aeronautics and Space Administration [NASA], *Spacecraft Sees Solar Storm Engulf Earth*, August 2011, http://science.nasa.gov/science-news/science-at-nasa/2011/18aug_cmemovie/.

5 NASA, *Solar Shield – Protecting the North American Grid*, October 2010, http://science.nasa.gov/science-news/science-at-nasa/2010/26oct_solarshield/.

6 NASA, *Solar Cycle 24 begins*, January 2008, http://science.nasa.gov/science-news/science-at-nasa/2008/10jan_solarcycle24/.

7 Ibid.

8 NASA, *Solar Shield – Protecting the North American Grid*, October 2010, http://science.nasa.gov/science-news/science-at-nasa/2010/26oct_solarshield/.

9 Ibid.

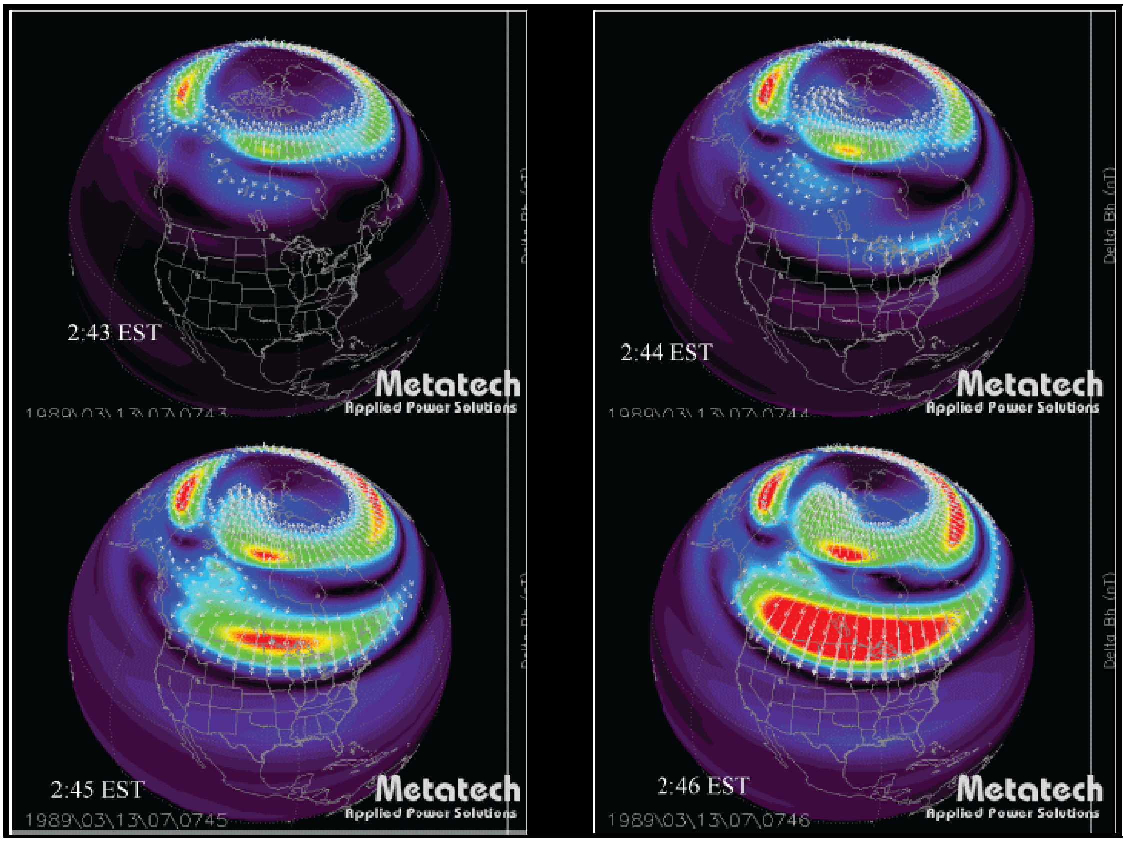
10 National Research Council, *Severe Space Weather Events – Understanding Societal and Economic Impacts*, 2008, http://www.nap.edu/catalog.php?record_id=12507.

11 NASA, *Solar Shield – Protecting the North American Grid*, October 2010, http://science.nasa.gov/science-news/science-at-nasa/2010/26oct_solarshield/.

12 National Research Council, *Severe Space Weather Events – Understanding Societal and Economic Impacts*, 2008, http://www.nap.edu/catalog.php?record_id=12507.

sufficient time to intervene, causing the entire grid to collapse in less than two minutes.[13] The bulk power system design acted to limit the physical damage to equipment, allowing power to be restored to about 83% of the affected customers within nine hours. However, "two large generator set-up transformers were damaged to overvoltage conditions."[14] Figure 2 illustrates the development of the 1989 geomagnetic disturbance over a period of four minutes.

Figure 2 – Development of Electrojet Conditions over Four Minutes (2:43–2:46 EST) Along the Canada–U.S. border, Leading to Hydro Québec Collapse and Other Reported Problems in Minnesota, Manitoba and Ontario at These Times



Source: The North American Electric Reliability Corporation.

The 1989 solar storm damaged transformers in "Quebec, New Jersey, and Great Britain, and caused more than 200 power anomalies across the USA from the eastern seaboard to the Pacific Northwest."[15] Similarly, a series of solar geomagnetic storms in October 2003 "triggered a regional blackout in southern Sweden and may have damaged transformers in South Africa."[16]

13 The North American Electric Reliability Corporation [NERC] and the U.S. Department of Energy [DOE], *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System – A Jointly-Commissioned Summary Report of the North American Electric Reliability Corporation and the U.S. Department of Energy's November 2009 Workshop*, June 2010, http://www.nerc.com/files/HILF.pdf.

14 Ibid.

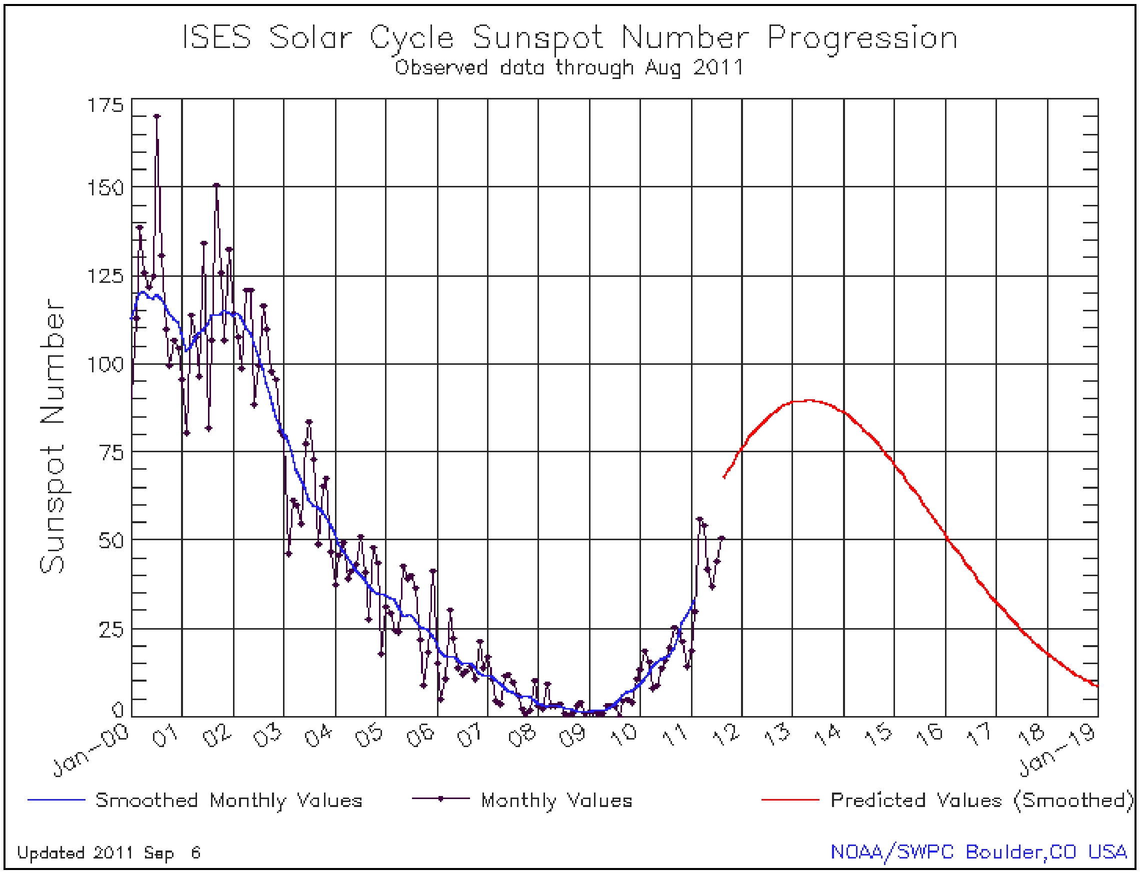
15 NASA, *Solar Shield – Protecting the North American Grid*, October 2010, http://science.nasa.gov/science-news/science-at-nasa/2010/26oct_solarshield/.

16 Ibid.

VULNERABILITY TO SOLAR GEOMAGNETIC DISTURBANCES

Forecasters predict that the current solar magnetic cycle will peak during the years around 2013 (Figure 3). According to NASA, while this peak will probably not be the biggest peak on record, "the basics of daily life – from communications to weather forecasting to financial services – depend on satellites and high-tech electronics," which increases the vulnerability of human society to solar storms.[17] Recent analyses of geomagnetic disturbance data indicate that "impulsive disturbances larger than 2000 nT/min [i.e., roughly four times larger than the March 1989 disturbance] have been observed on at least three occasions since 1972 at latitudes of concern for the North American bulk power system."[18] According to a 2008 report by the National Academy of Sciences, "a century-class solar storm can cause billions in economic damage."[19]

Figure 3 – Observed Solar Cycle Sunspot Number Progression, January 2000–August 2011



Source: Space Weather Prediction Centre.

17 NASA, *Space Weather turns into and International Problem*, July 2010, http://science.nasa.gov/science-news/science-at-nasa/2010/16jul_ilws/.

18 NERC and the DOE, *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System – A Jointly-Commissioned Summary Report of the North American Electric Reliability Corporation and the U.S. Department of Energy's November 2009 Workshop*, June 2010, http://www.nerc.com/files/HILF.pdf.

19 NASA, *Space Weather turns into and International Problem*, July 2010, http://science.nasa.gov/science-news/science-at-nasa/2010/16jul_ilws/ (The National Academy of Sciences report is available at http://www.nap.edu/catalog.php?record_id=12507#toc).

Even though North America's bulk power system is capable of handling familiar threats, such as equipment failure, human error and severe terrestrial weather conditions, it is "not designed to operate through the simultaneous loss of many key assets" which may result from geomagnetic disturbances that can develop rapidly with "continental footprints."[20] According to recent studies, North American power networks have become increasingly vulnerable to the impacts of severe geomagnetic disturbances due to a number of reasons:[21]

- To meet North America's growing electricity demand, the high voltage transmission grid has grown tenfold between Solar Cycle 19 in the late 1950s and Solar Cycle 22 in the early 1980s, which increased the system's size, complexity, interconnectedness, and, therefore, vulnerability to continental geomagnetic disturbances.
- The operating levels of high-voltage networks increased from 100–200 kV (kilovolt) design thresholds in the 1950s to 345–765 kV extra-high-voltage levels in today's networks. Higher voltage ratings are less resistant to geomagnetic disturbances, and, therefore, attract a higher concentration of GIC flow (e.g., 765kV lines would produce 10 times the GIC flow that 115 kV lines would produce for the same geomagnetic disturbance). This fact also makes the system more vulnerable to simultaneous outages in multiple major transmission lines, which have higher kV ratings than smaller lines.
- The concentration of GIC flow in the high-voltage portions of the power grid exposes large, extra-high voltage (EHV) transformers to larger GIC flows than their design structure can endure. "Previous well-documented cases [of geomagnetic disturbances] have noted heating failures that caused melting and burn-through"[22] in large, heavy-duty transformers. The failure of an EHV transformer has a higher impact on the power system than that of a comparable lower-voltage transformer (e.g., a 765 kV transformer will have about six times larger reactive power losses for the same GIC flow than a 115 kV transformer). Furthermore, EHV transformers generally cannot be repaired on-site, and if damaged, need to be replaced with new units, which have manufacture lead times of 12–24 months.
- "The ability to assess existing transformer vulnerability or … to design new transformers to be tolerant of saturated operation is not readily achievable"[23] due to the numerous subtle variations in the design of individual transformers – even when produced by the same manufacturer.
- The increasing efficiency of the power network in the last two decades has allowed the electric sector to increase their loads on key transmission lines in order to improve the efficiency of the power transfer between key generation and demand centres, and thereby reduce operational costs. While the sector's increased use of major transmission lines does not generally result in reliability impacts, it "could potentially complicate response procedures to a sudden or un-announced geomagnetic disturbance."[24]
- Some protection systems that are designed to address localized and isolated failures and irregularities along the network can exacerbate the overall responsive capacity of the bulk power system in the case of simultaneous failures of multiple components throughout the grid.[25]

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20 NERC and the DOE, *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System – A Jointly-Commissioned Summary Report of the North American Electric Reliability Corporation and the U.S. Department of Energy's November 2009 Workshop*, June 2010, http://www.nerc.com/files/HILF.pdf.

21 Ibid.

22 Ibid.

23 Ibid.

24 Ibid.

25 Ibid.

The impact of (and vulnerability to) a future solar storm will depend on a number of variables, including the size, location and pattern of the potential ensuing geomagnetic disturbance.[26] The vulnerability to solar storms is exacerbated by the current limited capacity to predict space weather, particularly pertaining to the sun-Earth system. According to NASA, predicting solar activity is a complex task involving multiple variables and interactions between the sun and Earth that "top scientists struggle to understand even with the aid of Earth's most powerful supercomputers."[27]

PREPAREDNESS TO GEOMAGNETIC DISTURBANCES

Following the March 1989 storm, industry took a number of actions to improve North America's response to solar geomagnetic disturbances. Most notably:

- Hydro-Québec instituted a number of technical measures to decentralize and reduce the impacts of a geomagnetic disturbance on the bulk power system, including new operating procedures and monitoring mechanisms.
- The Northeast Power Coordinating Council (NPCC), which works on improving the reliability of the interconnected bulk power system in North-eastern North America, contracted with Solar Terrestrial Dispatch[28] to implement a regional solar notification and communication system, known as the Geomagnetic Storm Mitigation System (GSMS).[29] NPCC jurisdictions,[30] which include Ontario, Quebec, New Brunswick and Nova Scotia, receive continuous updates on the status of solar activity, as well as geometric storm alerts, including visual and audible alarms and detailed information about any possible solar activity.[31]
- The NPCC published procedures that establish protective measures to minimize the vulnerability of the bulk power system to geomagnetic disturbances in the event of a solar storm.[32]

Through the Department of Natural Resources Canada (NRCan), the Geological Survey of Canada (GSC) conducts hourly forecasts of solar geomagnetic activity, based on data from 12 observatories across Canada and various sources around the world. GSC forecasts are based on "geomagnetic activity for up to two days in the future." The GSC issues warnings if solar events are found to meet predefined criteria, indicating a large enough risk to Canada's infrastructure.[33]

In addition to these efforts, NASA is working on improving the forecasting of future solar storms. Most notably, it has developed an experimental forecasting system, known as Solar Shield, which may be

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26 Ibid.

27 NASA, *Space Weather turns into and International Problem*, July 2010, http://science.nasa.gov/science-news/science-at-nasa/2010/16jul_ilws/.

28 Solar Terrestrial Dispatch is a privately owned space weather services company offering professional space weather services to commercial entities around the world. For more information, see http://www.spacew.com/.

29 NERC and the DOE, *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System – A Jointly-Commissioned Summary Report of the North American Electric Reliability Corporation and the U.S. Department of Energy's November 2009 Workshop*, June 2010, http://www.nerc.com/files/HILF.pdf.

30 The NPCC geographic region includes: New York State, the six New England states, Ontario, Quebec, New Brunswick and Nova Scotia.

31 The Northeast Power Coordinating Council [NPCC], *Procedures for Solar Magnetic Disturbances Which Affect Electric Power Systems* (last revised in January 2007), https://www.npcc.org/Standards/Procedures/c-15.pdf.

32 The NPCC procedures are available at https://www.npcc.org/Standards/Procedures/c-15.pdf.

33 The NPCC, *Procedures for Solar Magnetic Disturbances Which Affect Electric Power Systems*, last revised in January 2007, https://www.npcc.org/Standards/Procedures/c-15.pdf.

able to predict the vulnerability of individual transformers along the North American power grid to a solar geomagnetic disturbance. Using existing satellites, Solar Shield tracks CMEs through several points along their journey towards Earth's orbit, creating 3D models and predicting their arrival time to Earth. At 1.5 million kilometres upstream from Earth (approximately 30 minutes before impact), *in situ* measurements from the ACE spacecraft record the CME's speed, density, and magnetic field, which allows NASA to estimate the GICs and subsequently alert the appropriate utility operators. According to NASA's October 2010 Press Release, Solar Shield has never been field-tested during a sever geomagnetic storm. More field data is required to confirm the system's predictions.[34]

According to the North American Electric Reliability Corporation (NERC), geomagnetic storm operating procedures have allowed the electric sector to perform reliably through all geomagnetic disturbances since the March 1989 solar storm. However, NERC affirms that "the storms of concern could potentially be four to ten times more intense than March 1989 and could entail the potential for widespread damage to EHV transformers and other key assets of unprecedented proportions."[35]

PROPOSALS FOR FUTURE ACTION

In June 2010, the North American Electric Reliability Corporation (NERC) and the U.S. Department of Energy (DOE) published a jointly-commissioned report of their 2009 workshop on high-impact, low-frequency event risk to the North American bulk power system. The report presented five "Proposals for Action" concerning solar geomagnetic disturbances (Appendix A), including the creation of a government-industry taskforce that should identify prioritized mitigation steps that are "cost-effective and sufficient" to protect the power system in the event of a major geomagnetic disturbance. Based on our research, an assessment of the funds required to ensure the protection of critical infrastructure seems premature at this time.

34 NASA, *Solar Shield – Protecting the North American Grid*, October 2010, http://science.nasa.gov/science-news/science-at-nasa/2010/26oct_solarshield/.

35 NERC and the DOE, *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System – A Jointly-Commissioned Summary Report of the North American Electric Reliability Corporation and the U.S. Department of Energy's November 2009 Workshop*, June 2010, http://www.nerc.com/files/HILF.pdf.

APPENDIX A – SUMMARY OF PROPOSALS FOR ACTION[36]

1. NERC, working with its stakeholders, the U.S. DOE, and appropriate government authorities in Canada should create a task force of industry, equipment manufacturers, and risk experts to evaluate and prioritize mitigation and restoration options for Geomagnetic Disturbances (GMD), High-altitude Electromagnetic Pulse (HEMP) events, and Intentional Electromagnetic Interference (IEMI) threats, while recognizing the similarities and differences of these three severe electromagnetic threats. Focus should be given to identifying the prioritized "top ten" mitigation steps that are cost-effective and sufficient to protect the power system from widespread catastrophic damage due to each of these threats. The task force should consider the options and concepts discussed in this workshop report, including:
   - Define the protection environment for each of the electromagnetic threats, considering the work recently completed by the U.S. Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack (U.S. EMP Commission)14, the National Academy of Sciences15, FERC and the Federal Emergency Management Agency (FEMA).
   - Consider the tradeoffs of economic efficiency and reliability of the power system with regard to these electromagnetic threats using risk-based analysis. Cost estimates of potential mitigations provided by the EMP Commission should be revisited to appropriately account for labour, engineering, installation, and associated operating costs.
   - Identify the primary interdependencies with the other critical infrastructures that will impact restoration and reconstitution, with focus on telecommunications and fuel supply and delivery. Encourage cross-sector coordination to ensure the response of these assets to a GMD or HEMP attack is understood and that appropriate protections are put in place.
   - Evaluate the effectiveness of existing blackstart procedures, and the need for exercises for a case where the blackout area is extremely large and other infrastructures have been damaged. Develop new procedures if required.
   - Consider the need to develop a full "defense plan" that considers prevention, blackstart analysis, restoration, etc. to establish a model checklist/procedure for sector entities to deal with each of the threats.
2. Governmental authorities in the U.S. and Canada should continue to support industry efforts to address these risks. An executive order from government leaders, such as the President of the United States, would give additional weight to the importance of these issues relative to other priorities in both the public and private sectors.
3. Appropriate government authorities (to potentially include the U.S. DOE, FERC, DHS, NOAA, and National Aeronautics and Space Administration (NASA), and appropriate government authorities in Canada) should work with research organizations and the private sector to consider a roadmap for long-term research, development, and deployment on mitigating options for these threats. These efforts should be coordinated with NERC and the electric sector.
4. NERC, the U.S. FERC, DOE, DHS, NOAA, and NASA, and appropriate government authorities in Canada, together with subject matter experts, should work together to recommend the development of advanced methods to ensure system operators are given region-specific, timely, and accurate information regarding the expected duration, intensity, and geographic footprint of impending geomagnetic disturbances. Focus should be given to both extreme events and long duration, low-intensity storms.

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36 NERC and the DOE, *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System – A Jointly-Commissioned Summary Report of the North American Electric Reliability Corporation and the U.S. Department of Energy's November 2009 Workshop*, June 2010, http://www.nerc.com/files/HILF.pdf.

5. The U.S. DOE, DHS and appropriate government authorities in Canada, together with subject matter experts, should work together to establish an alert procedure to inform the electric sector that threat levels of an HEMP or IEMI attack have increased or that an attack is imminent. The communications method developed to distribute information concerning an impending geomagnetic storm or other critical infrastructure protection information could be used to disseminate these notices.