The Vulnerability of the US Electric Power Grid to Space Weather and the Role of Space Weather Forecasting

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Before the
U.S. House Subcommittee on Environment, Technology, and Standards
And the Subcommittee Hearing on
"What is Space Weather and Who Should Forecast It?"
October 30, 2003

I am grateful for the Committee's kind invitation to offer testimony today on "What is Space Weather and Who Should Forecast It?" as the answer to this important question has many possible implications and places the nation at an important crossroad. It is only fitting that we carefully consider the future path that is in the best interests of the nation. And as I hope to emphasize in my testimony, these space weather concerns, especially in regards to impacts on electric power grids, may pose important homeland security and energy security concerns and should be considered in your deliberations.

BACKGROUND
For the past 27 years, I have been an active researcher and observer of electric power system impacts caused by the widespread geomagnetic field disturbances due to Space Weather. For some 22 years, these activities occurred while I was employed in the electric power industry itself. I not only lead research investigations funded by my employer, but also efforts funded by the Electric Power Research Institute. My areas of responsibility involved the design and development of the high voltage transmission network and one of our pressing concerns was the unique problems posed by the natural phenomena of Space Weather. This was a problem that we recognized was of a growing and evolving nature as our industry continued to grow in size and technological sophistication. I particularly became engaged with the NOAA-SEC in the aftermath of the great geomagnetic storm of March 13-14, 1989, a storm which produced historic impacts to the operations of power grids in the US and around the world. I was part of an electric power industry group that advocated the efforts such as the ACE satellite and resulting solar wind monitoring that have greatly improved the nation's capability to provide accurate short-term forecasts of severe geomagnetic storm events.

Since 1997, I have subsequently been employed with the Metatech Corporation and a part of what we now do is heavily involved with Space Weather and impacts on technology systems, particularly large power grids. Our company has in fact been involved in the vulnerability and risk assessment for the power grids in England and Wales, Norway, Sweden and portions of Japan. Metatech also provides continuous space weather forecasting services for the company that operates the electric power grid for England and Wales. Since May 2002, Metatech has been providing similar vulnerability and risk assessments for the US electric power grid to the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP Commission). The EMP Commission was established by Congress under the provisions of the Floyd D. Spence Defense Authorization Act of 2001, Public Law 106-398, Title XIV. The EMP Commission was chartered to conduct a study of the potential consequences of a high altitude nuclear detonation on the domestic and military infrastructure and to issue a report containing its findings and recommendations to the Congress, the Secretary of Defense, and the Director, FEMA. While the charter of this commission involved intentional electromagnetic attack on the US infrastructures primarily from a high altitude nuclear burst, the MHD (or magneto hydro dynamic) portion of this electromagnetic attack can be remarkably similar to the electromagnetic disturbance caused by the natural phenomena of Space Weather. As a result the Commission wisely investigated the plausible impacts due to severe geomagnetic storms on the US electric power infrastructure. The Commission has also closely coordinated with the NERC (North

American Electric Reliability Council) and their Critical Infrastructure Protection Advisory Group (CIPAG). This group has been continuously and fully vetted on the findings of the Commission directed investigations. While the Commission is not scheduled to report their findings back to Congress until approximately March of 2004, they have encouraged Metatech to freely share with the scientific community the investigation results related to severe geomagnetic storm events. As a result, as part of my prepared testimony, I will also provide the significant portions of these findings. However, at this point, I should caution that these reports will only be the opinion of Metatech as the Commission has not completed deliberations and will not formally issue findings until early next year.

In these diverse and various capacities it has been my privilege to work with the NOAA-SEC for many years as an end-user of their forecast services, a bulk data user and in some degrees a competitor to the SEC. In all cases we have developed a close partnership with this agency and its staff, a relationship that has clearly allowed for key advances in improving the geomagnetic storm forecasting capability for the electric power industry.

Space Weather, Impacts to Electric Power Systems and the Importance of Forecasting Services
The Committee has posed four questions which are designed to probe the topic area of Space Weather Forecasting Services and their importance to the reliability of the nation's electric power grid. I shall attempt to answer these through examples of historic events, examination of developing trends and operational procedures and efforts that have been made to model and extrapolate implications for severe storm scenarios.

Question 1. *Please provide an overview of how space weather can affect electric power grid systems, including examples of historical events that have caused problems.*

Space Weather is associated with ejection of charged particles from the Sun, which after colliding with the Earth's magnetosphere will produce significant disturbances in the normally quiescent geomagnetic field at the Earth's surface. These disturbances have caused catastrophic impacts to technology systems in the past (e.g., the power blackout in Quebec in March 1989). More importantly, as detailed examinations have been undertaken concerning the interaction of geomagnetic storm environments with power grids and similar infrastructures, the realization has developed that these infrastructures are becoming more vulnerable to disruption from electromagnetic interactions for a wide variety of reasons. This trend line suggests that even more severe impacts can occur in the future for reoccurrences of large storms.

An Overview of the US Electric Power Grid
While electricity customers receive power from the local distribution system (typical operating voltage of 15kV with step down to 120/240 volt), the backbone of the system is the high voltage transmission network. The primary AC transmission network voltages in the US are at 230kV, 345kV, 500kV and 765kV. These transmission lines and their associated transformers serve as the long distance heavy hauling arteries of electricity production in the US. A single 765kV transmission line can carry over 2000 MW of power, nearly 200 times what a typical 15kV distribution line which is the overhead line commonly used for residential distribution. Space Weather or geomagnetic disturbances directly attack this same high voltage transmission circulatory system and because both have continental footprints, these disturbances can rapidly erode reliability of these infrastructures and can therefore threaten widespread blackout for extreme disturbance events. The US electric power grid is the worlds most extensive, Figure 1 provides a map of the approximate location of the nearly 80,000 miles of 345kV, 500kV and 765kV transmission lines in the contiguous US.

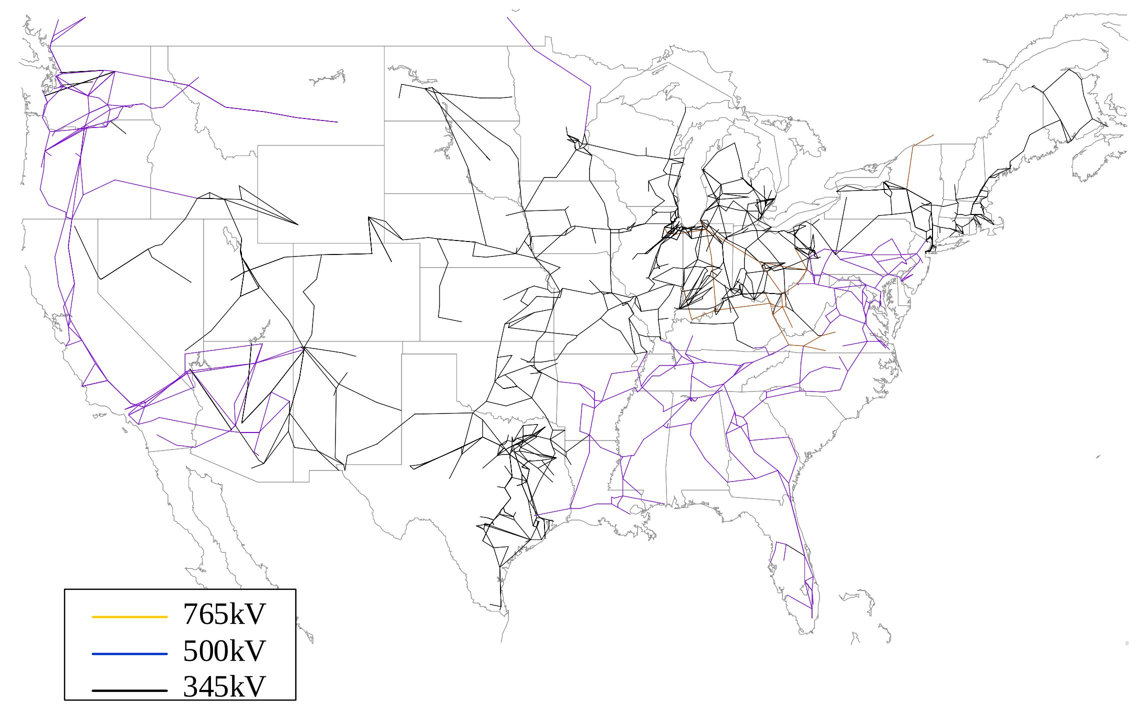


Figure 1: Map of 345kV, 500kV and 765kV transmission lines in contiguous US

These geographically wide spread assets are also fully exposed to the extremes of the terrestrial environments. Because these assets are the critical backbone of the system, utility company engineers have taken great care to engineer for robust capabilities of these assets to withstand most of the severe wind, lightning and ice loading exposures. For example, while many of the low voltage local distribution feeders can fail due to tree damage during hurricanes, these same hurricane events rarely threaten the integrity of the high voltage grid itself. While extensive attention has been paid to these assets for terrestrial weather exposures, a multitude of design decisions has inadvertently and significantly increased the power grid exposure and vulnerability to space weather environments, as will be discussed in later sections of this testimony. There are "no shortages" of challenges that these systems face. In addition to the terrestrial weather challenges, power company operators face even more ominous threats from the recent realization of physical and cyber terrorism. In spite of the best efforts, failures still can occur, for example a lightning strike can still cause on occasion a high voltage transmission line to trip. Very high winds, for example, due to a tornado can cause the failure of a line or several lines on a common corridor. However, most of these events generally occur in isolation and power grids are operated at all times to withstand the largest creditable single contingency failure without causing a cascading collapse of the network itself. Space Weather differs from ordinary weather in that it has a big footprint and attacks the system across many points simultaneously, causing at times of severe events multi-point failures on the network that can threaten the integrity of the network. Therefore, geomagnetic storms may be one of the most important hazards and is certainly the least understood threat that could be posed to the reliable operation of these networks.

The transmission lines and substations are all geographically remote and unstaffed facilities. They are difficult to fully monitor and cannot be continuously patrolled. The bulk of the protection of these facilities are done via autonomous relays that continuously sense for disturbance conditions and operate as quickly as 70 msec to trip off or isolate a asset that is sensed as an operating outside of acceptable parameters to protect the integrity of the network as a whole. Real-time data from a limited number of monitoring points is brought back to one of the more than 150 continuously-staffed control centers used to operate the transmission infrastructure in the US. There operators continually assess network conditions and make needed adjustments to keep all flows and voltages within prescribed boundaries and limits. Further they are responsible to dispatch generation (in many cases within a market-based supply system) to perfectly balance the production and demand for electric energy. The limited amount of real-time data makes it a challenge to fully assess the many possible threats that can occur to these remote assets. The remotely monitored data is not at all times unambiguous and can lead to differing interpretations. Therefore it is not easy to determine the nature of a threat from this alarm level information alone. In most control centers, the real-time data is typically augmented with continuous high quality terrestrial weather information, as regional storms and climatic events can be one of the most frequent sources of operational anomalies on the network. The power industry is just now getting to the point of being introduced to the same paradigm in regards to high-quality space weather data and the benefits it could offer in improving situational assessments.

The Electric Power Infrastructure and Its Sensitivity to Disturbance Levels

While more details will be provided later, a brief overview of how these geomagnetic disturbance environments actually interact with large regional power grids indicates the complex nature of the threat. When these disturbances occur they result in slowly varying (1 -1000 seconds) changes in the geomagnetic fields that can have very large geographic footprints. These magnetic field disturbances will induce electric fields in the Earth over these same large regions. Across the U.S., complex topologies of long-distance transmission lines have been built. These grids include transformers at generating plants and substations that have grounded neutrals. These transformer neutrals provide a path from the network to ground for these slowly varying electric fields (less than 1 Hz) to induce a current flow through the network phase wires and transformers.

These currents (known as geomagnetically-induced currents -- GICs) are generally on the order of 10's to 100's of amperes during a geomagnetic storm. Though these quasi-DC currents are small compared to the normal AC current flows in the network, they have very large impacts upon the operation of transformers in the network. Under normal conditions, even the largest transformer requires only a few amperes of AC excitation current to energize its magnetic circuit, which provides the transformation from one operating voltage to another. GIC when present, also acts as an excitation current for these magnetic circuits, therefore GIC levels of only 1 to 10 amperes can initiate magnetic core saturation in an exposed transformer. This transformer saturation from just a few amperes of GIC in modern transformers can cause increased and highly distorted AC current flows of as much as several hundred amperes leading to overloading and voltage regulation problems throughout the network.

Power networks for decades have been operated using what is termed an "N-1" operation criteria. That is, the system must always be operated to withstand the next credible disturbance contingency without causing a cascading collapse of the system as a whole. Therefore, when a single-point failure occurs, the system may need to be rapidly adjusted to be positioned to survive the next possible contingency. Space Weather disturbances have already been shown to cause near simultaneous multi-point failures in power system infrastructures, allowing little or no time for meaningful human interventions. The onset of severe geomagnetic field disturbances can be both sudden and have continental footprints, placing stresses broadly across power grid infrastructures.

When a transformer saturates, it can produce a number of simultaneous and undesired impacts to the grid. If the spatial coverage of the disturbance is large, many transformers (hundreds to thousands) will be simultaneously saturated. The principal concern to network reliability is due to increased reactive power demands from transformers that can cause voltage regulation problems, a situation that can rapidly escalate into a grid-wide voltage collapse. But a nearly equal concern arises from collateral impacts stemming from highly distorted waveforms (rich in harmonics) from saturated transformers that are injected into the network. As previously mentioned protective relays continuously sense these now distorted signals. These distortions can cause a mis-operation of an exposed relay causing it to operate to isolate a key element of the network. When these relay mis-operations occur in-mass because of the big footprint of a storm, the protection systems can rapidly destroy the integrity of the network that the relays were intended to protect. In addition, individual transformers may be damaged from overheating due to this unusual mode of operation, which can result in long-term outages to key transformers in the network.

The threats to the infrastructure from geomagnetic storms include the possibility of widespread power blackouts, damage to expensive and difficult to replace transformers, and damage to equipment connected to the grid. As a result, an important aspect of concern is the time required to replace damaged transformers and to fully restore the operation of the power grid.

Historic Storm Events and Power System Impacts

The rate of change of the magnetic field is a major factor in creating electric fields in the Earth and thereby inducing quasi-dc GIC current flow in the power transmission network. Therefore an important means of classifying the severity of a disturbance can be made by noting the dB/dt or rate-of-change of the geomagnetic field (usually measured in units of nanotesla per minute or nT/min). The larger this dB/dt environment becomes, the larger the resultant levels of GIC and levels of operational impact upon exposed power grids.

Some of the first reports of operational impacts to power systems date back to the early 1940's and the level of impacts have been progressively become more frequent and significant as growth and development of technology has occurred in this infrastructure. In more contemporary times, major power system impacts in the US have occurred in storms in 1957, 1958, 1968, 1970, 1972, 1974, 1979, 1982, 1983, and 1989 and several times in 1991. Smaller scale impacts can and do occur even more frequently, these include anomalous operating events that may result in the unexpected tripping of a key element of the system or even permanent damage to apparatus such as large power transformers.

In order to understand the far-reaching impacts of large geomagnetic storms, the disturbance impacts in particular of the great storm of March 13-14, 1989 are reviewed in some detail. The most important of these impacts was the storm-caused chain of events resulted in the blackout of the Hydro-Quebec power system. At 2:42 am EST, all operations across Quebec, Canada were normal. At 2:43 am EST, a large impulse in the Earth's magnetic field erupted along the U.S./Canadian border. GICs immediately started to flow in the southern portions of the Hydro-Quebec grid. In reaction to the GIC, voltage on the network began to sag as the storm increased in magnitude; automatic voltage compensating devices in the network rapidly turned "on" to correct this voltage imbalance. Unfortunately these compensators themselves were vulnerable to the harmonics generated in the network's transformers, and mis-operation of relays to protect these devices caused the entire fleet of 7 compensators on the network shut down within 60 seconds of the beginning of the storm impulse. When the compensators shut down, the network collapse followed within a matter of seconds putting over 6 million inhabitants of the province in the dark. Going from normal conditions to a complete province-wide blackout occurred in an elapsed time of just 90 seconds. The power system operators had no time to understand what was happening, let alone to take any meaningful human action to intervene and save the grid. In comparison, the August 14, 2003 blackout covering large portions of the US and Canada evolved over a period of time in excess of 90 minutes. Figure 2 provides a four minute sequence of maps showing the onset of observed geomagnetic field disturbance conditions that caused the Hydro Quebec blackout.

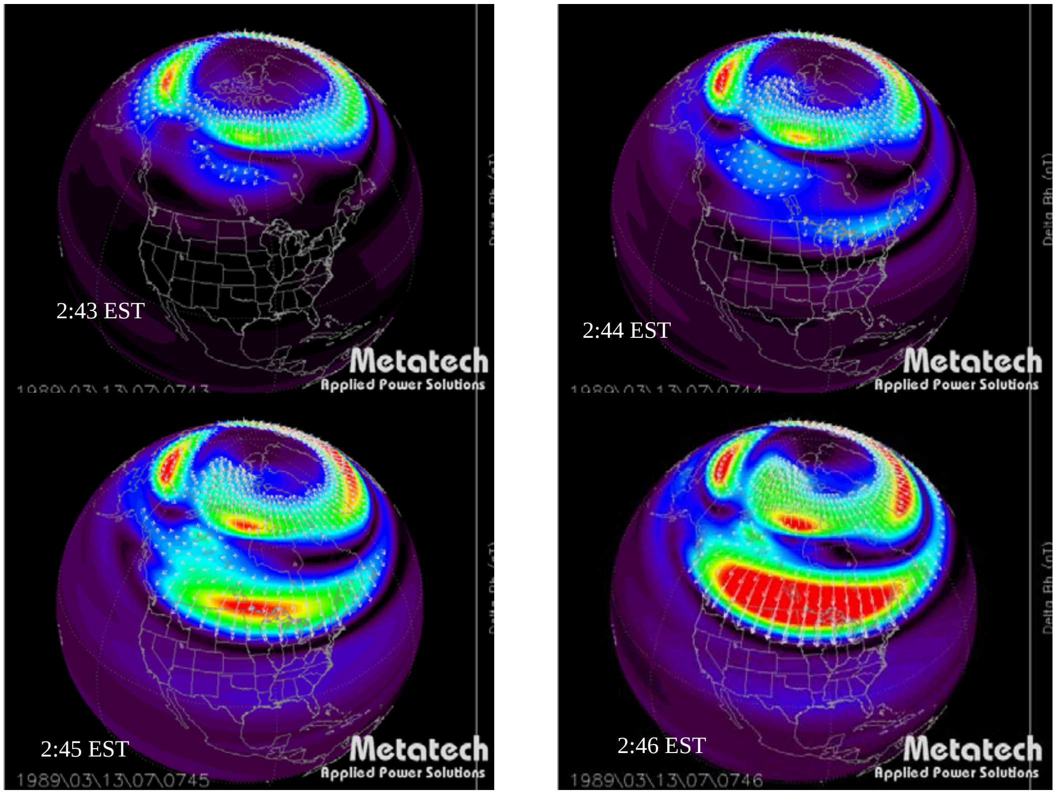
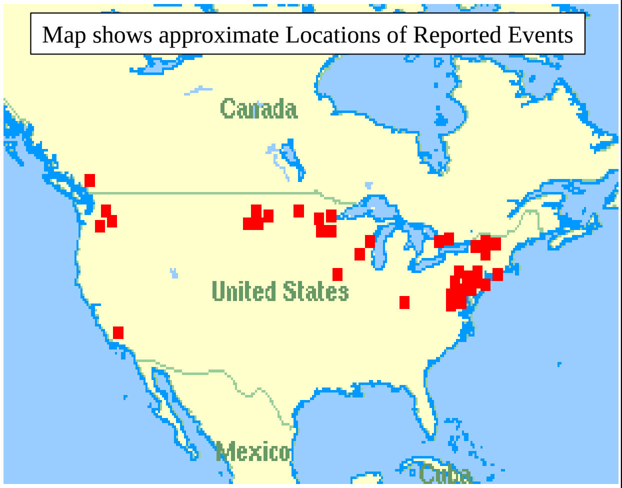


Figure 2. Rapid development of electrojet conditions over North America and principally along US/Canada border lead to Hydro Quebec collapse and other reported problems in Minnesota, Manitoba and Ontario at these times. These images depict the ground level geomagnetic intensification from over 4 Minutes from 2:43 – 2:46 EST

Over the next 24 hours, five additional magnetic disturbances propagated across the continent and nearly toppled power systems from the Midwest to the mid-Atlantic regions of the U.S. The North American Reliability Council (NERC), in their post analysis, attributed ~200 significant anomalies across the continent to this one storm. Figure 3 illustrates the geographic breadth of power system problems during one of the five substorm time periods on March 13, 1989 across the North American grid. Figure 4 provides a depiction of the geographic extent of the geomagnetic field disturbance conditions across North America at time 22:00UT, that triggered the events shown in Figure 3. As illustrated, at this time intense geomagnetic field disturbances extended into mid-latitude portions of North America and essentially across the entire US.

For further reference a list of the NERC reported power system operating anomalies due to this storm is provided in Exhibit 1. The North American Electric Reliability Council, at that time, would annually review significant system disturbances and provided a report on the most important of these system disturbances, in order to share information and insights on the disturbances and what lessons may be gained from these experiences. The 1989 System Disturbances report included discussions on the San Francisco Bay Area Earthquake, the impacts of Hurricane Hugo, and several other disturbances, most of which were tied to extreme environment disturbances. This report also provided a detailed discussion of the March 13-14, 1989 Geomagnetic Superstorm, which entailed ~50% of the entire 67 page NERC report. This Exhibit from that report provides an indication of the wide spread impacts that were observed across the continental power grid.



Time (EST)	Area	Event
1600	Atl. Elec.	MVAR
1602	Va. Pwr.	Capacitor
1610	PJM	Noise
1615	PJM	Generator
1625	PJM	Oscillograph
1626	PJM	Oscillograph
1630	SC Edison	Current
1630	SC Edison	Current
1630	SC Edison	Noise
1640	PJM	Voltage
1644	PJM	Alarm
1644	PJM	Capacitor
1645	WPL	Voltage
1649	PJM	Recorder
1651	NIMO	Capacitor
1653	NIMO	Capacitor
1654	PJM	Alarm
1655	Minn. Power	Voltage
1655	Atl. Elec.	Voltage
1665	Atl. Elec.	MVAR
1658	BC Hydro	Voltage
1658	OH	Demand
1658	WAPA	Converter
1658	BPA	Noise
1658	WAPA	Line
1658	WKPL	Alarm
1658	BPA	Capacitor
1658	BPA	Transformer
1700	UPA	Voltage
1700	LILCO	Voltage
1700	IIGE	Voltage
1700	WEP	Noise
1701	PJM	Capacitor
1701	NIMO	Capacitor
1701	Va. Pwr.	Capacitor
1701	Va. Pwr.	Capacitor
1701	OH	Voltage
1701	OH	Oscilligraph
1703	Va. Pwr.	Capacitor
1708	UPA	Capacitor
1709	WAPA	Converter
1709	WAPA	Transformer
1709	WAPA-Fargo	Voltage
1709	WAPA	Line
1709	WAPA	Relay
1711	NIMO	Capacitor
1720	UPA	Voltage
1723	Va. Pwr.	Capacitor

Figure 3. Reported North American power system impacts, March 13, 1989 time 16:00-17:23 EST (21:00-22:23 UT)

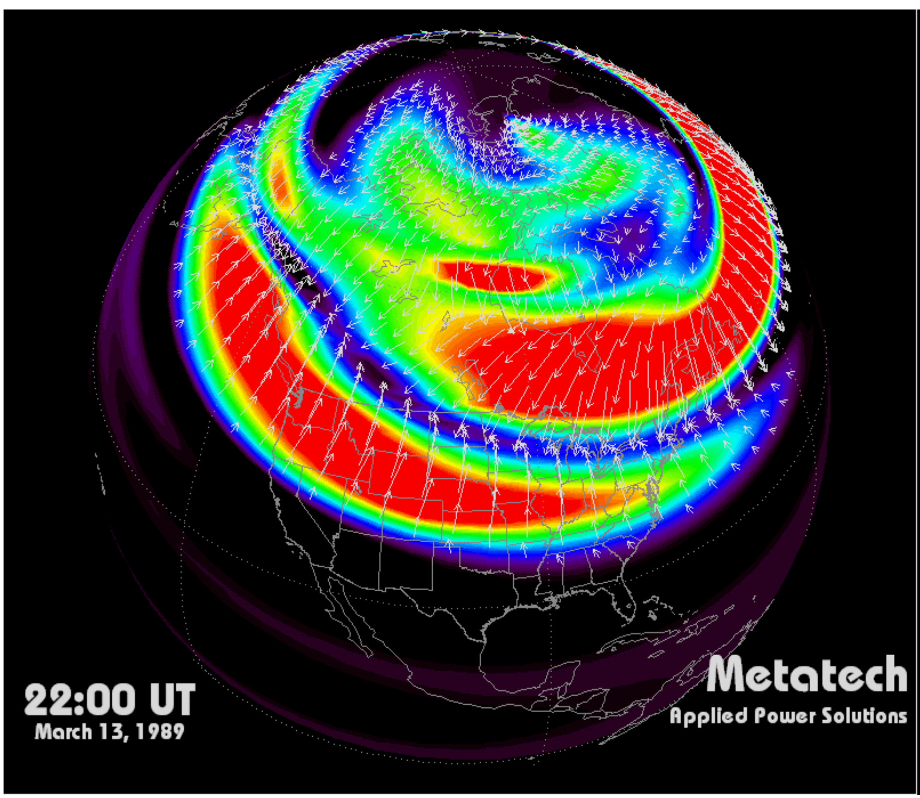


Figure 4. Estimated regions of observed geomagnetic field disturbance conditions at 22:00UT, March 13, 1989

As previously mentioned, the best means of characterizing the geomagnetic field disturbance environment as it relates to GIC impacts on power grids is the by the rate-of-change or dB/dt in nT/min. Figure 5 provides a plot of the dB/dt (or RGI- Regional GIC Index) observed at the Ottawa observatory which would have broadly characterized the intensity of the disturbance over the general New York, New England regions and neighboring portions of southern Ontario and Quebec in Canada.

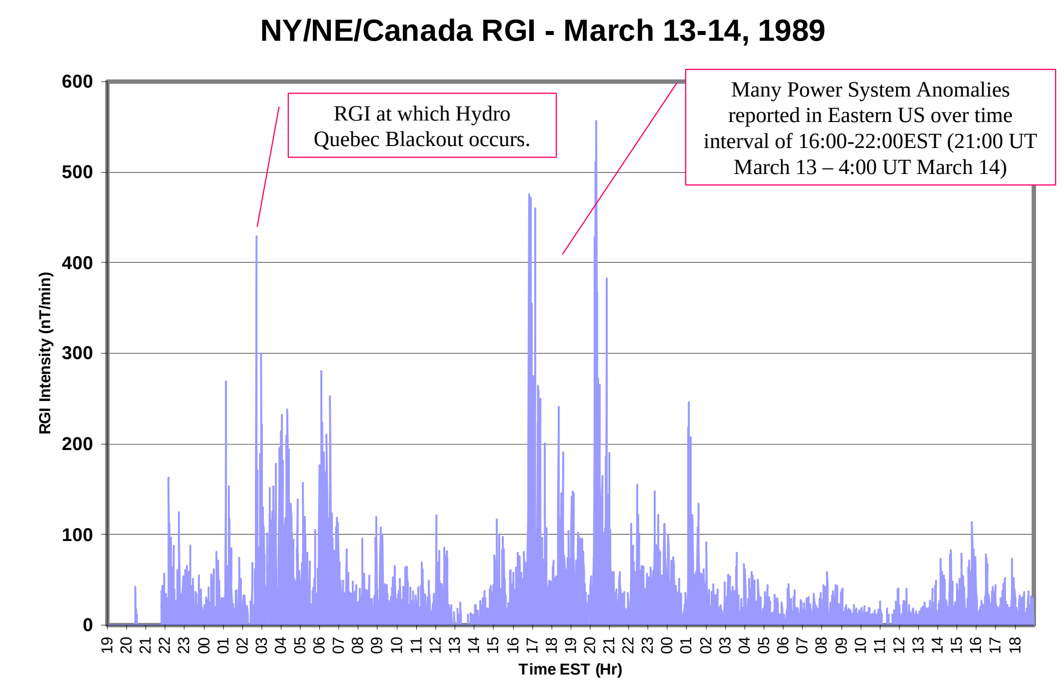


Figure 5. Observed Regional GIC Index (RGI) as measured at the Ottawa observatory on March 12-14, 1989

As shown, the disturbance intensity that triggered the Hydro Quebec collapse at 2:45 EST was at an intensity of ~480 nT/min. Over the time interval of power system events shown in Figure 3, the peak dB/dt disturbance intensities observed in various other locations across the US are provided in Figure 6. As shown, many of these disturbances were initiated by disturbance intensities that generally ranged between 300 and 600 nT/min.

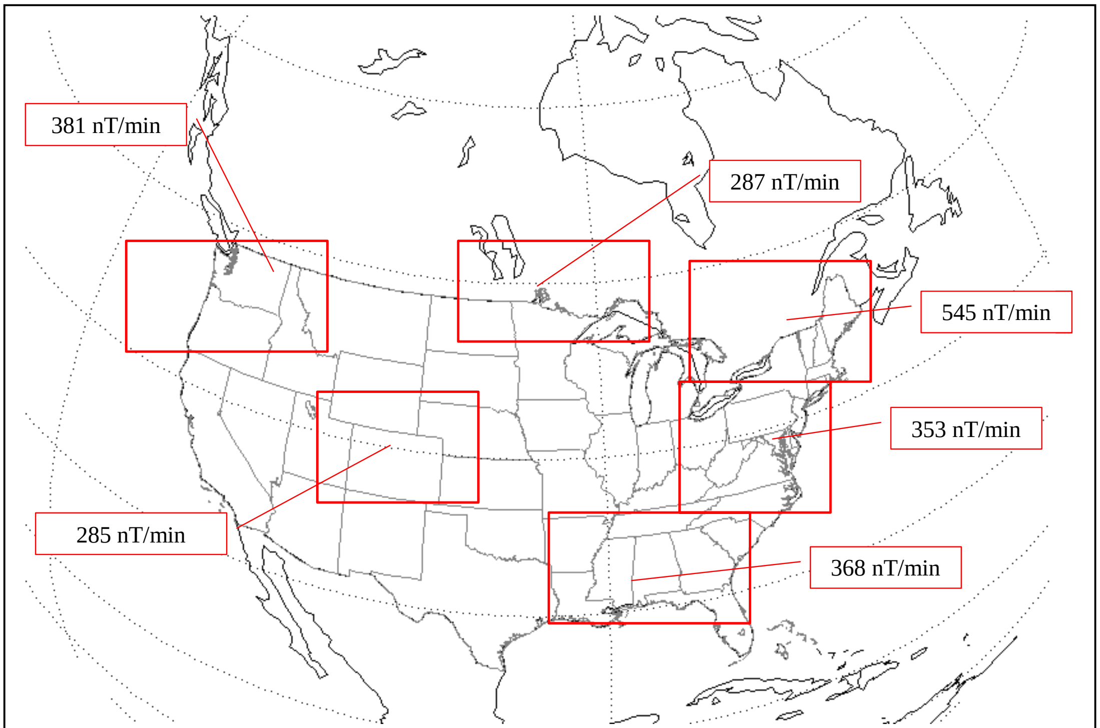


Figure 6. Disturbance Environments Observed by Region on March 13, 1989 during the 21:00 to 22:00 UT Substorm, Peak dB/dt in range from ~300 to ~600 nT/min

While power grid reliability concerns are of paramount importance, the long-duration of the storm and associated GIC's in transformers on the network caused internal transformer heating to the point of failure. There were several noteworthy cases of transformer internal heating associated with the March 13, 1989 storm in the US mid-Atlantic Region. In one case at the Salem Nuclear plant in southern New Jersey, the internal heating was so severe that complete failure of the transformer resulted. Figure 7 provides a few pictures of the transformer and internal winding damage (conductor melting and insulation burns) due to the GIC exposure. In this case the entire nuclear plant was unable to operate until the large 500kV ~1200MVA transformer was replaced. Fortunately a spare from a canceled nuclear plant in Washington State was available and restoration of the plant occurred in ~40 days. Transformers of this type are of custom design and in most cases new replacement transformers of this type generally take up to a year for delivery. Failures of key apparatus, such as this, raise concerns about the ability to rapidly restore power in a region once a blackout and failure has occurred.

Figure 7 – The Salem nuclear plant transformer (exterior shot is one of three phases) and two images of internal heating damage to conductors and insulation from stray flux heating caused by GIC-induced half-cycle saturation of the transformer occurring during the March 13-14, 1989 Superstorm.

Question 2. *How does your organization use data and products from NOAA's Space Environment Center (SEC)? In general, how much lead time do you need to make decisions for mitigating the effects of space weather?*

As I had previously discussed, I have had considerable experience both as an electric power industry user of data and products from the NOAA Space Environment Center as well as a provider of geomagnetic storm forecast services to electric power industry end-users. Therefore, if the Committee will allow me, I will attempt to answer this question from both points of perspective.

Electric Power Industry Application of Forecast Services

Some of the formative research and investigation of problems due to GIC in the power industry was undertaken by my colleague and mentor Professor Vernon D. Albertson at the University of Minnesota starting in the late 1960's. As a result of this work, formal arrangements were made to disseminate geomagnetic storm information provided by the US government (the SEC or forerunner in that era) through established communication means used to make coordinated adjustments in power grid frequency regulation for purposes of time error correction. AEP at that time acted as the official point of contact for these notifications from NOAA as noted in this circa 1987 NERC document provided in Exhibit 2. The March 1989 storm was the first storm to precipitate a large-scale blackout and very nearly threatened even wider scale problems across the US. This unprecedented level of impacts caused renewed emphasis on updating and revising operational procedures to better contend with the unknowns of the disturbance environments. In fact several example procedures for power pools heavily impacted by the March 1989 storm were published by NERC in the 1989 Disturbances Report as shown in Exhibit 3. These procedures and the regions they encompass include the NPCC, PJM, WAPA, and the Allegheny Power Service Corporation.

Overtime, these procedures have been continuously updated and current examples are provided for the PJM, NPCC, WSCC and even an updated reference document by the NERC as recent as July 17, 2003 and contemporaneous with the EMP Commission efforts to vet the NERC on US Electric Power Grid vulnerabilities to large geomagnetic disturbances. These examples are provided as Exhibits 4 to 7. These procedures describe some of the actions that operators would undertake to better prepare the system to contend with the anticipated stress caused by a storm. Even in the immediate aftermath of the March 1989 storm, the power industry came to recognize the need for predictive forecast warnings of these important storm events. In July 1990 the NERC Board of Trustees issued a position statement advocating forecast technologies that could provide approximately an hour advance notice of the occurrence of important storm events (see Exhibit 8).

Metatech and Other Commercially-Provided Forecasting Services for the Electric Power Industry
Because the NOAA-SEC provides only a broad and generic level of service to end users of space weather forecasts, these services are not well formatted to extrapolate the possible and plausible impacts that may result to complex technology systems such as electric power grids. As a result a need has developed and is being successfully filled by the private sector to provide highly specialized forecast services to these complex end users. At present this service sector is in a state of infancy, but is generally developing much along the model of the medical services community. In this case, the NOAA-SEC forecasts are the equivalent of the general practitioner, for those end users who have good space weather health (or at least suffer no serious space weather problems); this service may be quite adequate. However for end-users that have serious space weather health concerns, a more specialized care or level of service may be warranted and in most cases can be readily provided by firms such as ours that have specialized capabilities for these unique and complex problems. That being said, it should also be emphasized that end-user lack of awareness of potential space weather problems is a serious challenge that both the SEC and commercial providers must overcome. Exhibit 9 is a technical paper, which provides some commentary and overview on the type of specialized services that our company can and does provide to the electric power industry. The relevant portions of this paper discussing these forecast services start on approximately page 23 of the Exhibit. Metatech provides notifications that range from several days in advance based upon solar observations to short-term forecasts that can be on average an hour in advance driven by solar wind observations. We also provide continuous real-time observations as well to verify impacts that are being caused by a storm occurrence. We work extensively and very closely with our clients on their complex needs. These efforts can entail hardening their system from a design perspective; to training of system operators to operational prepare their system to better respond to anticipated and observed storm related stresses.

Even with these commercial capabilities, the NOAA-SEC provides some of the key data sources that become the input data that are used to drive these sophisticated forecast systems and services. Of necessity, the relationship between NOAA-SEC and the Commercial Providers is one that is highly symbiotic, it that the Commercial Providers greatly depend on the SEC for high quality data and data-interpretations, while the SEC looks to the commercial specialists to provide the more specialized services that heavily impacted users may need. Therefore, the loss of the NOAA-SEC would have the almost immediate impact of causing the crumbling of much of the forecasting services capability of the nation.

Question 3. *How would you compare our knowledge today of the impacts of space weather on electric power grid systems to what we knew five years ago, and to what we expect to know five years from now?*

> *New York ISO CEO William J. Museler in the aftermath of the August 14, 2003 Blackout, "the blackout could have damaged the power plants or transmission lines", "Had that kind of damage occurred, it could have taken days, weeks, or even months to restore. … This protection (meaning normal operation of relays that shut down the components on the grid) shortened the restoration process considerably".*

Advances in Understanding of Space Weather Impacts to Power Systems over the Past Five Years

There have been significant new findings and ever evolving understanding of the many facets of the complex space weather environment dynamics and the manner in which this impacts the operation of electric power grids. Mitigation of the impacts of these storms will depend heavily on forecast assessments of the onset, severity and regional manifestations of these storms and it is fair to say that much has also been achieved in this regard. While we can be proud of our accomplishments, there remains many unresolved space weather paradoxes of storm evolution and the manner in which they can degrade operations of infrastructures. In particular to the electric power grids, the major achievements can be summarized as follows, with supporting exhibits that elaborate further on many of these main items.

- Integrated and detailed modeling of both complex geomagnetic disturbance environment and complex power grid topologies. These advances have allowed for extensive forensic analysis of historically important geomagnetic storms and their impacts on power grids.
- Improved understanding, as described above, has allowed us to develop much more accurate and detailed quantification of the areas of risk and vulnerability that Space Weather may pose to the US power grid infrastructure. Surprisingly, we are now discovering that risks from storms are not just limited to high latitude located power grids, locations normally associate with auroral observations. New understandings indicate that highly developed power grids at all latitudes may be impacted by various space weather disturbance processes in the US and around the world that were unknown to us just a few years ago.
- These models and environment interaction understandings have also allowed the power industry to understand other aspects of evolving power grid vulnerability to the space weather environment that were not fully understood heretofore. The studies, which are part of the findings from the EMP Commission investigations, indicate that over the past several decades, various design decisions and growth of the power grid infrastructure has caused growing vulnerability to geomagnetic storms. In short over the past ~50 years, the size of the power grid has grown by nearly tenfold, and has also grown in sophistication such that it now presents a larger effective antenna to electromagnetically couple with geomagnetic storm disturbances. This has the affect of amplifying storm-caused disturbances in modern power systems. This vulnerability increase is not just limited to improved coupling due to larger grid size but also due to other related infrastructure design decisions, as more fully described in a recent article in Exhibit 9. The industry is also facing growing vulnerability to space weather events due to operational impacts that are occurring from deregulation and transitioning to market-based operation of the power grid. The recent blackout of August 14, 2003 highlighted many of the infrastructure and power market operational concerns. These concerns include continued large growth in electric power demand in the face of diminishing growth in the transmission network infrastructure needed for delivery of power. As a result, power pools such as PJM report for example in year 2000, the pool experienced a total of 3830 hours transmission network constraint operation[1]. In other words, ~44% of the year power flows on the transmission system were at or very near maximum levels. These congestion problems only worsened in 2001 as the hours of congestion of the real-time market increased to 4823 hours (~55% of the year)[2]. This heavy loading is another way of saying that the system is stressed to the safe operating limits and therefore unable to readily counter or safely absorb added stress to these same assets that could occur due to large geomagnetic storms. A recent article, Exhibit 10, provides a more detailed commentary on "What's Wrong with the Electric Grid". While it does not speak to the subject of space weather, it concisely describes the added burdens on today's transmission network infrastructure, the same portion of the infrastructure impacted by space weather events.

[1] PJM Interconnection State of the Market Report 2000, June 2001
[2] PJM Interconnection State of the Market Report 2001, June 2002

- The same efforts to evaluate impacts and risks of today's infrastructures have also allowed us to examine the plausible risks that could result from historically large storms that have not yet been experienced by today's power grid infrastructure. These studies were an especially important focus of the EMP Commission investigations that have been underway for the past 18 months. The results indicate that major power grid operational impact threats loom due to these low probability, but very large storm events. For instance, we have examined in detail the specifics of the March 1989 super storm and as previously discussed witnessed unprecedented power system impacts for storm intensities that reached levels of approximately 300 to 600 nT/min. However, the investigation of very large storms have made us newly aware that storm intensities over many of these same US regions could be as much as 4 to 10 times larger. This increase in storm intensity causes a nearly proportional increase in resulting stress to power grid operations. These storms also have a footprint that can simultaneously threaten large geographic regions and can therefore plausibly trigger even larger regions of grid collapse than what occurred on August 14, 2003. Exhibit 12 is a brief opinion article that discusses the context of the events leading up to the August 14, 2003 blackout and how such a scenario could in the future be triggered by a space weather storm. Exhibit 13 provides a more detailed summary of investigations undertaken on the US power grid for impacts caused by very large geomagnetic storm events. As shown in this series of studies, disturbance impacts to power grid operations could plausibly be 3 to 10 times larger in the US than those experienced in the March 1989 super storm. This paper shows one of many possible scenarios for how a large storm could unfold. As illustrated in Figure 8, a large region of power system collapse is projected for severe geomagnetic disturbance scenarios. Depending on the morphology of the geomagnetic disturbance, it would be conceivable that a power blackout could readily impact areas and populations larger than those of the recent August 14, 2003 blackout.

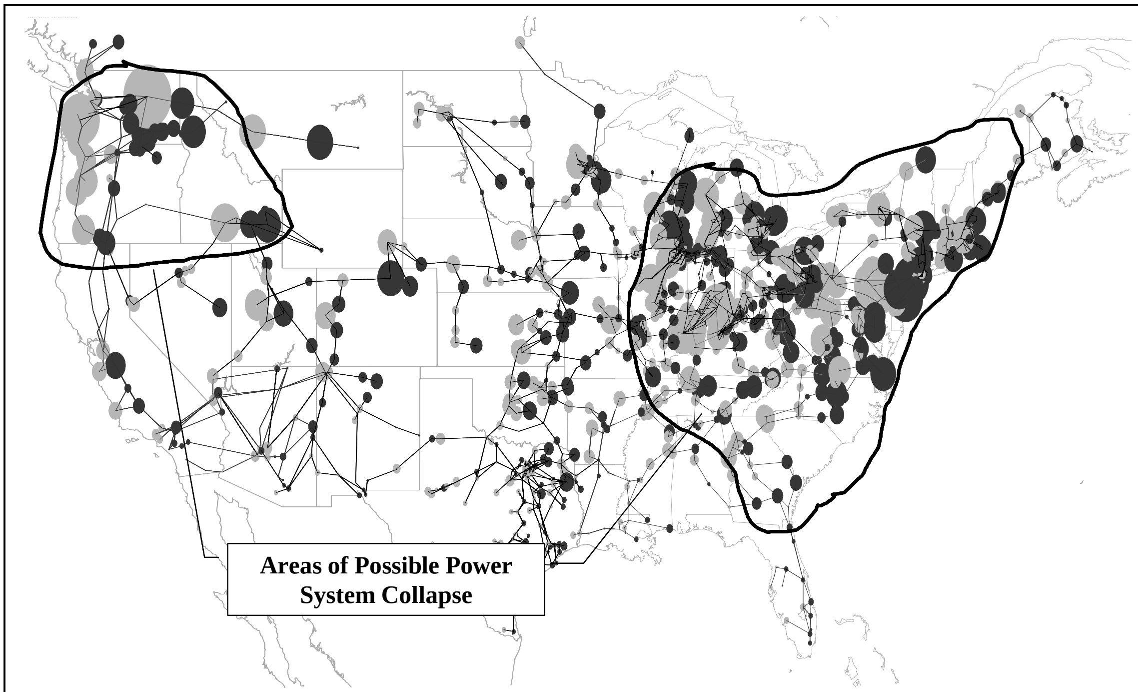


Figure 8 – US Electric Power Grid simulation results showing regions of large GIC flows and possible power system collapse due to a 4800 nT/min disturbance scenario. Other scenarios changing the location or the disturbance footprint could lead to differing regions of power system collapse.

While these complex models have been rigorously tested and validated, this is an exceedingly complex task with uncertainties that can easily be as much as a factor of two. However, just empirical evidence alone suggests that power grids in North America that were challenged to collapse for storms of 400 to 600 nT/min over a decade ago, are not likely to survive the plausible but rare disturbances of 2000 to 5000 nT/min that long term observational evidence indicates have occurred before and therefore may be likely to occur again.

Because large power system catastrophes due to Space Weather are not a zero probability event and because of the large-scale consequences of a major power grid blackout, I am compelled to add some commentary on the potential societal and economic impacts of such an event should it ever re-occur. The August 14, 2003 event provides a good case study; the utilities and various municipal organizations should be commended for the rapid and orderly restoration efforts that occurred. However, we should also acknowledge that in many respects this blackout occurred during highly optimal conditions that were somewhat taken for granted and should not be counted upon in future blackouts. For example, an outage on January 14 rather than August 14 could have meant coincident cold weather conditions. Under these conditions, breakers and equipment at substations and power plants can be enormously more difficult to re-energize when they become cold. This can translate into the possibility of significantly delayed restorations. Geomagnetic storms as previously discussed can also permanently damage key transformers on the grid, which further burdens the restoration process. For that matter, these conditions could rapidly cause serious public health and safety concerns, in that people trapped in regions such as New York City would not have the option of a "Night in Central Park Experience" and perhaps not be able to easily find adequate shelter from the elements. The time of day when the outage occurred was also a significant advantage, in that the bulk of the utility company day-crews were still available and able to be readily dispatched to perform restoration functions. In major cities, the blackout essentially brought to a halt most transportation systems. All mass-transit systems shutdown as they depend on electricity for many of their functions. Traffic signal systems on most major streets and highways stopped and as a result most major thoroughfares became the equivalent of 8 lane parking lots in the early hours of the blackout. Only a few major power facilities are continuously manned, and since blackouts are possible at any hour, the odds are that ~75% of the time the normal utility day crews are not on the job when these events occur. Attempting to recall workers that are trapped on the wrong side of these transportation snares is highly problematic.

In many respects, the loss of power supply returns much of our society to a pre-industrial era, because the loss of power supply rapidly cascaded into many other infrastructures. For example, water and sewage plants and transportation systems generally shutdown across the affected regions, even some 911 emergency systems and communication systems were impacted. Power grids are arguably the most important of the critical infrastructures because most of the other critical infrastructures are so highly interdependent on reliable power supply from the grid. It is clearer now that the technology age has increased our reliance on electric power. Figure 9 shows a chart plotting the primary interdependency links that exist between electric power and other critical infrastructures and services such as water, transportation, telecommunications and fuel supplies. As this illustrates, electric power supply is central to the sustained operation of most of the nation's other critical infrastructures.

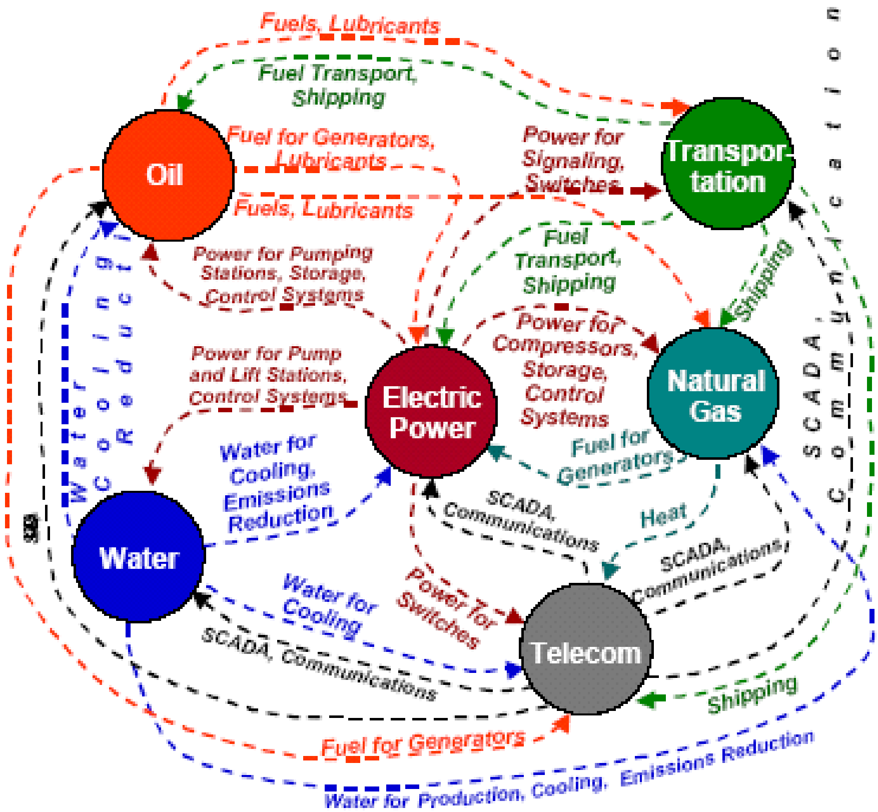


Figure 9 – Electric Power and other major infrastructure interdependency plot. Courtesy US DOE

Only a small portion of these infrastructure facilities have emergency on-site generation of sufficient capacity that allows them to continue operation in the face of a blackout event. Water treatment and pumping require enormous amounts of electric power and as result very few of these systems have redundant power supply options. Loss of pumping in time will lead to drop of city water pressure, as storage tanks and reservoirs cannot be recharged for residential distribution. In large high-rise buildings, city supply water pressure needs to be supplemented with electric pumps to lift water to upper floors for water distribution. Therefore within a matter of a few hours potable water distribution in many locations can become a serious concern. Perishable foods are generally at risk of complete loss within 12 hours or less. As previously discussed, transportation of all types was seriously impacted. Even automobiles and trucks could only operate within the range of the fuel in their tank at the time, because nearly all refueling operations from underground storage tanks require restoration of electric power supply.

Most affected regions were restored within approximately 24-36 hours after the blackout. As described in hearings on October 20 before the House Financial and Banking Infrastructure Committee, the major telecommunications (not counting wireless-cellular phone systems) and interdependent financial systems were able to maintain many functions. However, this was due to backup generation at a few critical hubs, which generally have around 72 hours of available fuel. Therefore power grid outages of longer durations would be highly problematic in that refueling may be logistically impossible in all situations. W. A. Abernathy, the Assistant Secretary for Financial Institutions, cautioned in his testimony that our financial institutions primarily operate on the principle of confidence, "*confidence that financial transactions will be carried out, that checks will clear, that bills will be paid, that investments will be made, that insurance promises will be kept. The confidence provided by financial institutions and their services play a big part in helping to cope with the trauma of disaster.*" An event which causes the eventual cessation of these functions, even for a short time, in key financial centers could have potential for wide spread consequences to the economy.

Because of the possible large geographic laydown of a severe storm event and resulting power grid collapse, the ability to provide meaningful emergency aid and response to an impacted population that may be in excess of 100 million people will be a difficult challenge. Potable water and replenishment of foods may need to come from boundary regions that are unaffected and these unaffected regions could be very remote to portions of the impacted US population centers. As previously suggested adverse terrestrial weather conditions could cause further complications in restoration and re-supply logistics.

Space Weather and Power System Understandings – The Future

Given the surprising and potentially enormous implications of recent power system threats due to space weather, it is difficult to accurately predict what the future may bring. However, the future of space weather is being shaped, in fact, by activities that are underway today. Much good work is underway to continue efforts such as described here to further understand and evaluate the potential impacts of large storm events. While having the ability to accurately assess threats to these infrastructures is an important accomplishment, the real payoff of this capability is in the application of this knowledge towards engineering solutions that reduce the risks. In order to protect against the effects from severe geomagnetic storms, several approaches may need to be used. In terms of the entire grid itself, remedial measures to reduce GIC levels may be needed, such as installation of supplemental transformer neutral ground resistors to reduce GIC flows and undo this unintended geomagnetic antenna that has developed as the industry has built the present day high voltage transmission grid in the U.S. Grid operational measures can be better evaluated and tested for the multitude of scenarios and procedures enhanced to prevent severe voltage regulation problems in order to preserve the integrity of the network as a whole. This means that additional generation capacity and fast-acting voltage compensating reserves should be available and/or loads should be rapidly removed from the system. This requires advanced information and contingency planning by the power utilities. With the aid of continuous solar wind monitoring, it is possible to reliably predict the onset of a storm 30 to 45 minutes in advance. This is due to the availability of real-time satellite data and modeling capabilities that are now within the state of the art. These capabilities are reasonably expected to further improve within the next five years, but only as long as the nation maintains a commitment to gather the observational data and disseminate it for the forecast models that can use it.

Question 4. *What would be the impact to your organization and the electric power grid industry if the SEC were no longer able to provide its space weather forecasts to you? Please provide specific examples when possible.*

In response to this question, let me first speak to the impacts upon the power industry should the SEC or the nation's space weather forecast capability cease to exist. As previously discussed, the power industry has been aware of the potential for some large impacts due to storms and as recent discoveries indicate, these threats have the potential to be even more ominous in their implications that previously understood. It is also clear that the vulnerability that presently exists has evolved due to long term trends and that these trends because they involve embedded designs to billions of dollars in assets cannot be undone overnight. The most effective mitigation strategy in the short term and perhaps in the long term is improved situational awareness for operators of these systems from evolving space weather disturbances and then attempting to counter some of the impacts by providing more robust operational postures in anticipation of storm-caused impacts.

In the era prior to solar wind monitoring and the advances in improved solar activity monitoring, storm events would often blindside operators with sudden onsets. Unlike most terrestrial weather, these events develop suddenly once the threatening inputs from solar activity arrive at the Earth. The loss of these capabilities would return us to the 1980's, where all that existed in many respects was a monitoring service and storm information for the most part arrived *after-the-fact* and therefore could not be usefully utilized to avoid significant operational impacts, rather the information just confirmed for operators what caused any impacts and only marginally better prepared them for additional impacts from the same storm. Therefore, power grids would have to rely almost exclusively on their own power grid monitors for the first signs of possible storm impacts. However, these would be a poor substitute in most respects and would create a number of operator uncertainties and paradoxes. The operators would not be able to receive advance notice of severe impacts that appear with sudden onsets. For storm events that have slower evolution, it would take some time to determine if operating anomalies are due to a geomagnetic storm or some other event. Once they determine that it is a geomagnetic storm then it would be necessary to be overly cautious and restrictive for many additional hours of small storm activity because it would be difficult to know if a larger storm development is possible. In the aftermath of the Hydro Quebec collapse, the operators of that system based operational procedures on observations of local activity. In 1991, they spent nearly 10% of the year in geomagnetic storm operating posture and as a result reduced substantially their ability to transfer large blocks of power across their network and export it outside their system. In today's more volatile electric energy markets, such operating postures could produce substantial added hours of constricted operation of networks and have immediate cost impacts on real-time electric energy markets. An example of this type of energy market cost impact can be illustrated by a storm on July 15, 2000 and the response of the power market when the PJM power pool declared a storm emergency. On July 15, 2000, the PJM declared an SMD emergency beginning at 15:30 and declared an end to the SMD emergency at time 21:07, resulting in a period of ~6 hours of emergency conditions in which PJM follows prescribed procedures for network conservative operation as described in Sections 3-1 to 3-5 of the PJM Operations Manual. During this ~6 hour period, the real-time price increased approximately $40/MWH on average. Under conservative operation, the operation of the power network biases towards security and reliability of the network as a whole rather than just economic dispatch. As a result, transfers across the network can be significantly reduced, leading to re-dispatch of generation and cost increases in the real-time market due to less optimal economics in the dispatch of generation in this security mode of operation. Even though this storm event occurred under light load and highly favorable market conditions, the cumulative real-time market cost increase totaled ~$900,000. Storm assessment uncertainties can extend longer than necessary operation of the network in these restricted market conditions and add even more to these cost impacts. During some periods of the day, energy cost increases can be much more severe and total costs could be even higher as a result. Of course, the economic and societal costs of large-scale failures in the US power grid overwhelm all other cost concerns and forecast efforts provided to prevent that scenario from being realized should be of paramount concern.

Metatech is dependent for many of the forecast products we supply upon reliable, high-cadence and high quality data from the SEC as needed inputs into the models and forecast systems we operate. In response to cessation of the SEC functions, we would have to significantly alter and as a result diminish the quality of some of the services we could provide. In addition, I would suspect that some commercial providers may choose to simply exit the business in response and others that might have been willing to enter the business will instead decide not to do so. Further, it would be unlikely at this time that any commercial provider would decide to enter the market to shoulder the heavy burden of launching satellites and setting up and coordinating various world observatories needed to provide important data inputs. In short, the customers, no matter who the provider, would have fewer options available to them and would receive an overall lower quality of service. Lacking any official government agency responsible for space weather forecasting, a likely development at times will be the equivalent of a "Tower of Babel", where information is widely scattered amongst a large number of government, military and international observation sites and each speaking in a differing tongue as to their interpretation and not one of them having complete enough information to develop a useful "Big Picture" of the unfolding space weather events.

Even the idea of a successor agency being handed the responsibility that currently resides with the SEC has a number of potential impact consequences. No matter how dedicated the new responsible agency, there will be unavoidable losses in the transition. Any new organization would need to successfully overcome the added start-up hurdles before even considering how best to meet the challenges of forecasting a difficult space weather environment. Since our company has commercial responsibilities similar to the associated activities that the SEC must perform to deliver their products, I can certainly state that an operation such as this has many high maintenance and expensive tasks. This includes such unglamorous but vital back office and field tasks such as data collection, quality control of the data and, finally, timely data dissemination. These all need the continuity of an experienced and capable staff of unsung heroes to assure the high level of reliability and availability that has been provided by the SEC. These systems, of course, need to work in harmony with the derived products and forecast services that are the more familiar face of the SEC. As I have emphasized previously in my testimony, the space weather disturbances we are attempting to forecast can have amazingly rapid onsets and can manifest as a diverse variety of consequences to large geographic regions. Therefore forecast staff needs to be highly trained and experienced so they can quickly assess and judge, as there is no time for hesitancy and uncertainty. Further all this needs to be done on a continuous 24 hour by 7-day per week basis, as the Sun never sets on the nation's threats from Space Weather disturbances. As you can surmise, setting up a new function such as this is not a matter of buying a few servers, installing some shrink-wrap, and parking some people in front of a monitor. Nearly every function that is done involves much in the way of custom systems and a high degree of specialized human "know how". Therefore the loss of the highly trained and experienced staff would be an unfortunate loss of investment by the nation and setback our collective capabilities in space weather forecasting.

In conclusion I would also like to offer a perspective on the long term needs that should further be considered by this Committee in supporting our nation's efforts to better mitigate concerns arising from space weather events. For example, the degree of deterioration in the reliability of the electric power grid has been a topic of considerable discussion, post August 14, 2003. It is now evident that uncertainty in long term restructuring, and lack of transmission infrastructure investment were significant factors contributing to the events of that day. Yet no matter how maligned, this infrastructure is still capable of operating through "single-point" failures. In contrast, our nation's most important space weather monitoring assets have no redundancy in case of failure. A loss, for example, of the NASA-ACE solar wind monitoring satellite (at the vital L1 position in space) would largely deprive the nation of the ability to perform high quality short term forecasting of geomagnetic storms. The end of lifetime for ACE is rapidly approaching and still no formal plans exist by any government agency in the world for a replacement satellite. Other examples also exist for various other observation assets that supply needed data inputs to our space weather forecast systems. Our grasp on the ability to perform these vital functions can be lost at any moment in time and we may not be able to recover for a number of years in some cases. Therefore I would also like to urge the Committee to consider these future "heavy lifting" responsibilities in sustaining and improving our nation's space weather infrastructure, once we get past this current SEC funding crisis.

Listing of Exhibits to Prepared Testimony of John G. Kappenman

Exhibit 1: Chronology of Reported Events, NERC Disturbance Analysis Working Group Report, "The 1989 System Disturbances: March13, 1989 Geomagnetic Disturbance," pages 55-60, 1990.

Exhibit 2: NERC Appendix 7B — Notification of Solar Magnetic Disturbance Warnings, December 1, 1987.

Exhibit 3: Practices and Procedures for Dealing with Geomagnetic Disturbances, NERC Disturbance Analysis Working Group Report, "The 1989 System Disturbances: March13, 1989 Geomagnetic Disturbance," pages 53-54, 1990.

Exhibit 4: PJM Emergency Operations Manual, Section 3: Conservative Operations, Solar Magnetic Disturbances, pages 3-4 and 3-5, Revision 13, Effective Date 01/01/03.

Exhibit 5: Procedures for Solar Magnetic Disturbances Which Affect Electric Power Systems, Document C-15, Northeast Power Coordinating Council, Revised Nov. 7, 2000.

Exhibit 6: WSCC PROCEDURE FOR NOTIFICATION AND REPORTING OF SOLAR MAGNETIC DISTURBANCES (SMD), Approved by Board of Trustees, August 7, 2001.

Exhibit 7: NERC, Geomagnetic Disturbance Reference Document, Version 1, Approved by Operating Committee July 16 – 17, 2003.

Exhibit 8: NERC Position Statement on Solar Magnetic Disturbance Forecasting, Approved by the Board of Trustees, July 9, 1990.

Exhibit 9: J.G. Kappenman, "An Introduction to Power Grid Impacts and Vulnerabilities from Space Weather", NATO-ASI Book on Space Storms and Space Weather Hazards, edited by I.A. Daglis, Kluwer Academic Publishers, NATO Science Series, Vol. 38, pg 335-361, 2001.

Exhibit 10: J.G. Kappenman, "Electric Power Grids and Evolving Vulnerability to Space Weather", feature article for AGU International Journal of Space Weather, in press 2003.

Exhibit 11: Eric J. Lerner, "What's Wrong with the Electric Grid?", The Industrial Physicist, American Institute of Physics, pages 8-13, October/November 2003.

Exhibit 12: J.G. Kappenman, "Opinion: Systemic Failure on a Grand Scale – August 14, 2003", signed opinion article for AGU International Journal of Space Weather, in press 2003.

Exhibit 13: J.G. Kappenman, "Space Weather and the Vulnerability of Electric Power Grids", in *Effects of Space Weather on Technology Infrastructure*, edited by I. A. Daglis, Kluwer Acad., Norwell, Mass., in press, 2003.