SEVERE SPACE WEATHER EVENTS—

UNDERSTANDING SOCIETAL AND ECONOMIC IMPACTS

A WORKSHOP REPORT

Committee on the Societal and Economic Impacts of Severe Space Weather Events: A Workshop

Space Studies Board

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Summary

SOCIETAL CONTEXT

Modern society depends heavily on a variety of technologies that are susceptible to the extremes of space weather—severe disturbances of the upper atmosphere and of the near-Earth space environment that are driven by the magnetic activity of the Sun. Strong auroral currents can disrupt and damage modern electric power grids and may contribute to the corrosion of oil and gas pipelines. Magnetic storm-driven ionospheric density disturbances interfere with high-frequency (HF) radio communications and navigation signals from Global Positioning System (GPS) satellites, while polar cap absorption (PCA) events can degrade—and, during severe events, completely black out—HF communications along transpolar aviation routes, requiring aircraft flying these routes to be diverted to lower latitudes. Exposure of spacecraft to energetic particles during solar energetic particle events and radiation belt enhancements can cause temporary operational anomalies, damage critical electronics, degrade solar arrays, and blind optical systems such as imagers and star trackers.

The effects of space weather on modern technological systems are well documented in both the technical literature and popular accounts. Most often cited perhaps is the collapse within 90 seconds of northeastern Canada's Hydro-Quebec power grid during the great geomagnetic storm of March 1989, which left millions of people without electricity for up to 9 hours. This event exemplifies the dramatic impact that extreme space weather can have on a technology upon which modern society in all of its manifold and interconnected activities and functions critically depends.

Nearly two decades have passed since the March 1989 event. During that time, awareness of the risks of extreme space weather has increased among the affected industries, mitigation strategies have been developed, new sources of data have become available (e.g., the upstream solar wind measurements from the Advanced Composition Explorer), new models of the space environment have been created, and a national space weather infrastructure has evolved to provide data, alerts, and forecasts to an increasing number of users.

Now, 20 years later and approaching a new interval of increased solar activity, how well equipped are we to manage the effects of space weather? Have recent technological developments made our critical technologies more or less vulnerable? How well do we understand the broader societal and economic impacts of extreme space weather events? Are our institutions prepared to cope with the effects of a "space weather Katrina," a rare, but according to the historical record, not inconceivable eventuality? On May 22 and 23, 2008, a workshop held in Washington, D.C., under the auspices of the National Research Council brought together representatives of industry, the federal government, and the social science community to explore these and related questions. This report was prepared by members of the ad hoc committee that organized the workshop, and it summarizes the key themes, ideas, and insights that emerged during the 1½ days of presentations and discussions.

THE IMPACT OF SPACE WEATHER

Modern technological society is characterized by a complex interweave of dependencies and interdependencies among its critical infrastructures. A complete picture of the socioeconomic impact of severe space weather must include both direct, industry-specific effects (such as power outages and spacecraft anomalies) and the collateral effects of space-weather-driven technology failures on dependent infrastructures and services.

Industry-specific Space Weather Impacts

The main industries whose operations can be adversely affected by extreme space weather are the electric power, spacecraft, aviation, and GPS-based positioning industries. The March 1989 blackout in Quebec and the forced outages of electric power equipment in the northeastern United States remain the classic example of the impact of a severe space weather event on the electric power industry. Several examples of the impact of space weather on the other industries are cited in the report:

- The outage in January 1994 of two Canadian telecommunications satellites during a period of enhanced energetic electron fluxes at geosynchronous orbit, disrupting communications services nationwide. The first satellite recovered in a few hours; recovery of the second satellite took 6 months and cost $50 million to $70 million.
- The diversion of 26 United Airlines flights to non-polar or less-than-optimum polar routes during several days of disturbed space weather in January 2005. The flights were diverted to avoid the risk of HF radio blackouts during PCA events. The increased flight time and extra landings and takeoffs required by such route changes increase fuel consumption and raise cost, while the delays disrupt connections to other flights.
- Disabling of the Federal Aviation Administration's recently implemented GPS-based Wide Area Augmentation System (WAAS) for 30 hours during the severe space weather events of October-November 2003.

With increasing awareness and understanding of space weather effects on their technologies, industries have responded to the threat of extreme space weather through improved operational procedures and technologies. As just noted, airlines re-route flights scheduled for polar routes during intense solar energetic particle events in order to preserve reliable communications. Alerted to an impending geomagnetic storm by NOAA's Space Weather Prediction Center (SWPC) and monitoring ground currents in real-time, power grid operators take defensive measures to protect the grid against geomagnetically induced currents (GICs). Similarly, under adverse space weather conditions, launch personnel may delay a launch, and satellite operators may postpone certain operations (e.g., thruster firings). For the spacecraft industry, however, the primary approach to mitigating the effects of space weather is to design satellites to operate under extreme environmental conditions to the maximum extent possible within cost and resource constraints. GPS modernization through the addition of two new navigation signals and new codes is expected to help mitigate space weather effects (e.g., ranging errors, fading caused by ionospheric scintillation), although to what degree is not known. These technologies will come on line incrementally over the next 15 years as new GPS satellites become operational. In the meantime, the Federal Aviation Administration will maintain "legacy" non-GPS-based navigation systems as a backup, while other GPS users (e.g., offshore drilling companies) can postpone operations for which precision position knowledge is required until the ionospheric disturbance is over.

The Collateral Impacts of Space Weather

Because of the interconnectedness of critical infrastructures in modern society, the impacts of severe space weather events can go beyond disruption of existing technical systems and lead to short-term as well as to long-term collateral socioeconomic disruptions. Electric power is modern society's cornerstone technology, the technology on which virtually all other infrastructures and services depend. Although the probability of a wide-area electric power blackout resulting from an extreme space weather event is low, the consequences of such an event could be very high, as its effects would cascade through other, dependent systems. Collateral effects of a longer-term outage would likely include, for example, disruption of the transportation, communication, banking, and finance systems, and government services; the breakdown of the distribution of potable water owing to pump failure; and the loss of perishable foods and medications because of lack of refrigeration. The resulting loss of services for a significant period of time in even one region of the country could affect the entire nation and have international impacts as well.

Extreme space weather events are low-frequency/high-consequence (LF/HC) events and as such present—in terms of their potential broader, collateral impacts—a unique set of problems for public (and private) institutions and governance, different from the problems raised by conventional, expected, and frequently experienced events. As a consequence, dealing with the collateral impacts of LF/HC events requires different types of budgeting and management capabilities and consequently challenges the basis for conventional policies and risk management strategies, which assume a universe of constant or reliable conditions. Moreover, because systems can quickly become dependent on new technologies in ways that are unknown and unexpected to both developers and users, vulnerabilities in one part of the broader system have a tendency to spread to other parts of the system. Thus, it is difficult to understand, much less to predict, the consequences of future LF/HC events. Sustaining preparedness and planning for such events in future years is equally difficult.

Future Vulnerabilities

Our knowledge and understanding of the vulnerabilities of modern technological infrastructure to severe space weather and the measures developed to mitigate those vulnerabilities are based largely on experience and knowledge gained during the past 20 or 30 years, during such episodes of severe space weather as the geomagnetic superstorms of March 1989 and October-November 2003. As severe as some of these recent events have been, the historical record reveals that space weather of even greater severity has occurred in the past—e.g., the Carrington event of 1859[1] and the great geomagnetic storm of May 1921—and suggests that such extreme events, though rare, are likely to occur again some time in the future. While the socioeconomic impacts of a future Carrington event are difficult to predict, it is not unreasonable to assume that an event of such magnitude would lead to much deeper and more widespread socioeconomic disruptions than occurred in 1859, when modern electricity-based technology was still in its infancy.

A more quantitative estimate of the potential impact of an unusually large space weather event has been obtained by examining the effects of a storm of the magnitude of the May 1921 superstorm on today's electric power infrastructure. Despite the lessons learned since 1989 and their successful application during the October-November 2003 storms, the nation's electric power grids remain vulnerable to disruption and damage by severe space weather and have become even more so, in terms of both widespread blackouts and permanent equipment damage requiring long restoration times. According to a study by the Metatech Corporation, the occurrence today of an event like the 1921 storm would result in large-scale blackouts affecting more than 130 million people and would expose more than 350 transformers to the risk of permanent damage.

SPACE WEATHER INFRASTRUCTURE

Space weather services in the United States are provided primarily by NOAA's SWPC and the U.S. Air Force's (USAF's) Weather Agency (AFWA), which work closely together to address the needs of their civilian and military user communities, respectively. The SWPC draws on a variety of data sources, both space- and ground-based, to provide forecasts, watches, warnings, alerts, and summaries as well as operational space weather products to civilian and commercial users. Its primary sources of information about solar activity, upstream solar wind conditions, and the geospace environment are NASA's Advanced Composition Explorer (ACE), NOAA's GOES and POES satellites, magnetometers, and the USAF's solar observing networks. Secondary sources include SOHO and

STEREO as well as a number of ground-based facilities. Despite a small and unstable budget (roughly $6 million to $7 million U.S. dollars annually) that limits capabilities, the SWPC has experienced a steady growth in customer base, even during the solar minimum years, when disturbance activity is lower. The focus of the USAF's space weather effort is on providing situational knowledge of the real-time space weather environment and assessments of the impacts of space weather on different Department of Defense missions. The Air Force uses NOAA data combined with data from its own assets such as the Defense Meteorological Satellites Program satellites, the Communications/Navigation Outage Forecasting System, the Solar Electro-Optical Network, the Digital Ionospheric Sounding System, and the GPS network.

NASA is the third major element in the nation's space weather infrastructure. Although NASA's role is scientific rather than operational, NASA science missions such as ACE provide critical space weather information, and NASA's Living with a Star program targets research and technologies that are relevant to operations. NASA-developed products that are candidates for eventual transfer from research to operations include sensor technology and physics-based space weather models that can be transitioned into operational tools for forecasting and situational awareness.

Other key elements of the nation's space weather infrastructure are the solar and space physics research community and the emerging commercial space weather businesses. Of particular importance are the efforts of these sectors in the area of model development.

Space Weather Forecasting: Capabilities and Limitations

One of the important functions of a nation's space weather infrastructure is to provide reliable long-term forecasts, although the importance of forecasts varies according to industry.[2] With long-term (1- to 3-day) forecasts and minimal false alarms,[3] the various user communities can take actions to mitigate the effects of impending solar disturbances and to minimize their economic impact. Currently, NOAA's SWPC can make probability forecasts of space weather events with varying degrees of success. For example, the SWPC can, with moderate confidence, predict the occurrence probability of a geomagnetic storm or an X-class flare 1 to 3 days in advance, whereas its capability to provide even short-term (less than 1 day) or long-term forecasts of ionospheric disturbances—information important for GPS users—is poor. The SWPC has identified a number of critical steps needed to improve its forecasting capability, enabling it, for example, to provide high-confidence long- and short-term forecasts of geomagnetic storms and ionospheric disturbances. These steps include securing an operational solar wind monitor at L1; transitioning research models (e.g., of coronal mass ejection propagation, the geospace radiation environment, and the coupled magnetosphere/ionosphere/atmosphere system) into operations, and developing precision GPS forecast and correction tools. The requirement for a solar wind monitor at L1 is particularly important because ACE, the SWPC's sole source of real-time upstream solar wind and interplanetary magnetic field data, is well beyond its planned operational life, and provisions to replace it have not been made.

UNDERSTANDING THE SOCIETAL AND ECONOMIC IMPACTS OF SEVERE SPACE WEATHER

The title of the workshop on which this report is based, "The Societal and Economic Impacts of Severe Space Weather," perhaps promised more than this subsequent report can fully deliver. What emerged from the presentations and discussions at the workshop is that the invited experts understand well the effects of at least moderately severe space weather on specific technologies, and in many cases know what is required to mitigate them, whether enhanced forecasting and monitoring capabilities, new technologies (new GPS signals and codes, new-generation radiation-hardened electronics), or improved operational procedures. Limited information was also provided—and captured in this report—on the costs of space weather-induced outages (e.g., $50 million to $70 million to restore the $290 million Anik E2 to operational status) as well as of non-space-weather-related events that can serve as proxies for disruptions caused by severe space storms (e.g., $4 billion to $10 billion for the power blackout of August 2003), and an estimate of $1 trillion to $2 trillion during the first year alone was given for the societal and economic costs of a "severe geomagnetic storm scenario" with recovery times of 4 to 10 years.

Such cost information is interesting and useful—but as the outcome of the workshop and this report make clear, it is at best only a starting point for the challenge of answering the question implicit in the title: What are the societal and economic impacts of severe space weather? To answer this question quantitatively, multiple variables must be taken into account, including the magnitude, duration, and timing of the event; the nature, severity, and extent of the collateral effects cascading through a society characterized by strong dependencies and interdependencies; the robustness and resilience of the affected infrastructures; the risk management strategies and policies that the public and private sectors have in place; and the capability of the responsible federal, state, and local government agencies to respond to the effects of an extreme space weather event. While this workshop, along with its report, has gathered in one place much of what is currently known or suspected about societal and economic impacts, it has perhaps been most successful in illuminating the scope of the myriad issues involved, and the gaps in knowledge that remain to be explored in greater depth than can be accomplished in a workshop. A quantitative and comprehensive assessment of the societal and economic impacts of severe space weather will be a truly daunting task, and will involve questions that go well beyond the scope of the present report.

NOTES

1. The Carrington event is by several measures the most severe space weather event on record. It produced several days of spectacular auroral displays, even at unusually low latitudes, and significantly disrupted telegraph services around the world. It is named after the British astronomer Richard Carrington, who observed the intense white-light flare associated with the subsequent geomagnetic storm.
2. For the spacecraft industry, for example, space weather predictions are less important than knowledge of climatology and especially of the extremes within a climate record.
3. False alarms are disruptive and expensive. Accurate forecasts of a severe magnetic storm would allow power companies to mitigate risk by canceling planned maintenance work, providing additional personnel to deal with adverse effects, and reducing the amount of power transfers between adjacent systems in the grid. However, as was pointed out during the workshop, if the warning proved to be a false alarm and planned maintenance was canceled, the cost of large cranes, huge equipment, and a great deal of material and manpower sitting idle would be very high.

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Future Solutions, Vulnerabilities, and Risks

The workshop session titled "The Future: Solutions or Vulnerabilities?" was intended to look into the future and evaluate how technical systems and their utilization are expected to evolve, and how this evolution affects their vulnerability to space weather. The technical infrastructure, enabling technologies, and space-based assets of the country are constantly changing. New electronic devices, new navigation systems, and new power grid systems are all evolving in response to improved technologies and increased requirements for efficiency and capability. Within this environment of innovation, designers will need to trade engineering solutions to mitigating space weather impacts against operational needs and space weather forecasting. This chapter addresses the evolution of current technologies and systems and their vulnerability to space weather, anticipated new technologies that may be more, or less, vulnerable to space weather than currently, and the estimation of future risks. Session panelists were asked to examine their industry with the understanding that we do not know the full range of possible space weather as demonstrated by the Carrington event of 1859, whose effects on Earth's magnetic field were far greater[1] than those of any magnetic storm in the space era, and by the solar radio burst on December 6, 2006, which was 10 times more intense than any previous solar radio burst recorded over the past 50 years.

The session's speakers each received questions, tailored to their particular expertise, that can be generally summarized as follows: (1) How will current technologies and systems evolve and what will be their vulnerability to space weather? (2) Can new technologies be expected that will be vulnerable to space weather? and (3) Will engineering solutions that mitigate space weather effects be possible and practical in the future?

The limitations of a workshop format allowed for a sampling of three technology infrastructure areas in this session. An analysis of electrical power systems was presented by John Kappenman of Metatech Corporation. Presentations on GPS and aviation systems were given by Thomas McHugh of the FAA and Christopher Hegarty of the MITRE Corporation. An analysis of satellite systems was presented by Ronald Polidan of Northrop Grumman Corporation. In addition, a presentation on estimating future extremes of space weather by T. Paul O'Brien from the Aerospace Corporation was presented by Joseph Fennell and is covered in this section. These presentations and the related workshop discussions are summarized below. In some cases the summarized material draws substantially from the abstracts of the presentations included in Appendix C.

POWER GRIDS

Future Vulnerability

Severe space weather has the potential to pose serious threats to the future North American electric power grid.[2] Recently, Metatech Corporation carried out a study under the auspices of the Electromagnetic Pulse Commission and also for the Federal Emergency Management Agency (FEMA) to examine the potential impacts of severe geomagnetic storm events on the U.S. electric power grid. These assessments indicate that severe geomagnetic storms pose a risk for long-term outages to major portions of the North American grid. John Kappenman remarked that the analysis shows "not only the potential for large-scale blackouts but, more troubling, . . . the potential for permanent damage that could lead to extraordinarily long restoration times." While a severe storm is a low-frequency-of-occurrence event, it has the potential for long-duration catastrophic impacts to the power grid and its users. Impacts would be felt on interdependent infrastructures, with, for example, potable water distribution affected within several hours; perishable foods and medications lost in about 12-24 hours; and immediate or eventual loss of heating/air conditioning, sewage disposal, phone service, transportation, fuel resupply, and so on. Kappenman stated that the effects on these interdependent infrastructures could persist for multiple years, with a potential for significant societal impacts and with economic costs that could be measurable in the several-trillion-dollars-per-year range.

Electric power grids, a national critical infrastructure, continue to become more vulnerable to disruption from geomagnetic storms. For example, the evolution of open access on the transmission system has fostered the transport of large amounts of energy across the power system in order to maximize the economic benefit of delivering the lowest-cost energy to areas of demand. The magnitude of power transfers has grown, and the risk is that the increased level of transfers, coupled with multiple equipment failures, could worsen the impacts of a storm event.

Kappenman stated that "many of the things that we have done to increase operational efficiency and haul power long distances have inadvertently and unknowingly escalated the risks from geomagnetic storms." This trend suggests that even more severe impacts can occur in the future from large storms. Kappenman noted that, at the same time, no design codes have been adopted to reduce geomagnetically induced current (GIC) flows in the power grid during a storm. Operational procedures used now by U.S. power grid operators have been developed largely from experiences with recent storms, including the March 1989 event. These procedures are generally designed to boost operational reserves and do not prevent or reduce GIC flows in the network. For large storms (or increasing dB/dt levels) both observations and simulations indicate that as the intensity of the disturbance increases, the relative levels of GICs and related power system impacts will also increase proportionately. Under these scenarios, the scale and speed of problems that could occur on exposed power grids have the potential to impact power system operators in ways they have not previously experienced. Therefore, as storm environments reach higher intensity levels, it becomes more likely that these events will precipitate widespread blackouts in exposed power grid infrastructures. The possible extent of a power system collapse from a 4800 nT/min geomagnetic storm (centered at 50° geomagnetic latitude) is shown in Figure 7.1. Such dB/dt levels—10 times those experienced during the March 1989 storm—were reached during the great magnetic storm of May 14-15, 1921.

The least understood aspect of this threat is the permanent damage to power grid assets and how that will impede the restoration process. Transformer damage is the most likely outcome, although other key assets on the grid are also at risk. In particular, transformers experience excessive levels of internal heating brought on by stray flux when GICs cause a transformer's magnetic core to saturate and to spill flux outside the normal core steel magnetic circuit. Kappenman stated that previous well-documented cases have involved heating failures that caused melting and burn-through of large-amperage copper windings and leads in these transformers. These multi-ton apparatus generally cannot be repaired in the field, and if damaged in this manner, they need to be replaced with new units, which have manufacture lead times of 12 months or more. In addition, each transformer design can contain numerous subtle design variations that complicate the calculation of how and at what density the stray flux can impinge on internal structures in the transformer. Therefore the ability to assess existing transformer vulnerability or even to design new transformers that can tolerate saturated operation is not readily achievable.

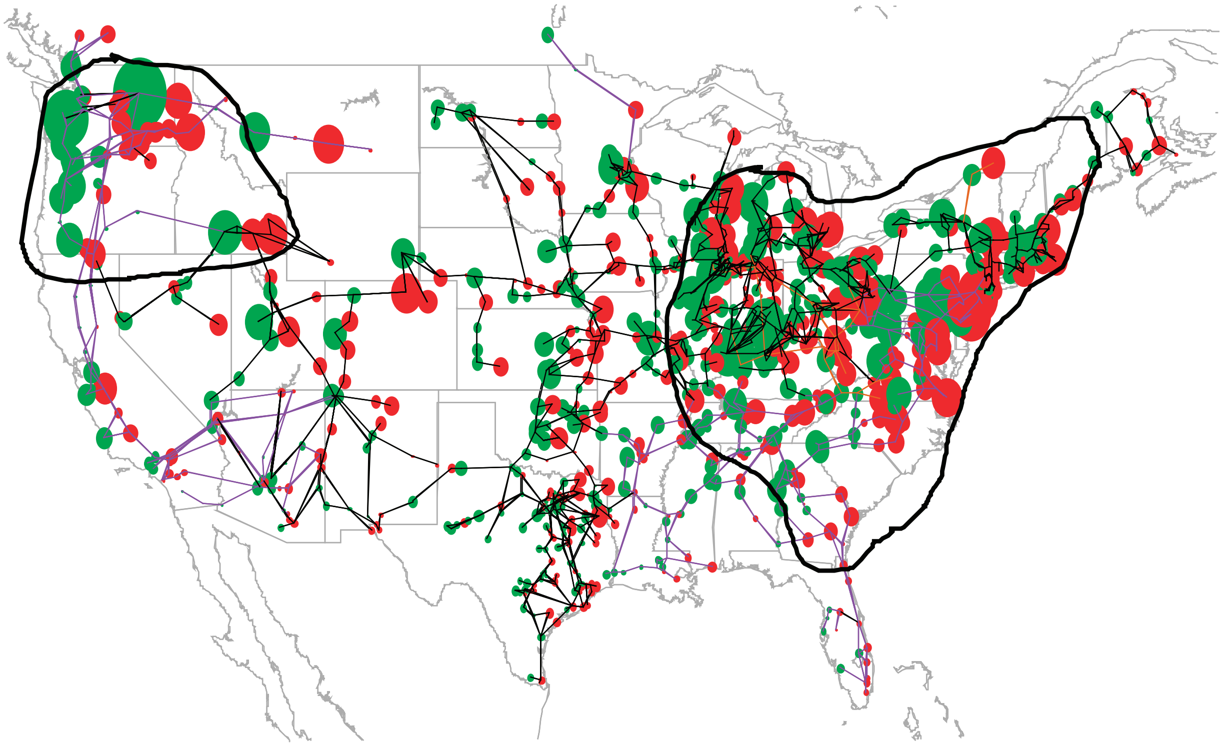

FIGURE 7.1 Scenario showing effects of a 4800 nT/min geomagnetic field disturbance at 50° geomagnetic latitude scenario. The regions outlined are susceptible to system collapse due to the effects of the GIC disturbance; the impacts would be of unprecedented scale and involve populations in excess of 130 million. SOURCE: J. Kappenman, Metatech Corp., "The Future: Solutions or Vulnerabilities?," presentation to the space weather workshop, May 23, 2008.

The experience from recent space weather events suggests a threatening outcome for today's infrastructure from historically large storms that are yet to occur.

Recent analysis by Metatech estimates that more than 300 large EHV transformers would be exposed to levels of GIC sufficiently high to place these units at risk of failure or permanent damage requiring replacement. Figure 7.2 shows an estimate of percent loss of EHV transformer capacity by state for a 4800 nT/min threat environment such as might occur during a storm of the magnitude of the May 1921 event. Such large-scale damage would likely lead to prolonged restoration and long-term shortages of supply to the affected regions.

In summary, present U.S. grid operational procedures are based largely on limited experience, generally do not reduce GIC flows, and are unlikely to be adequate for historically large disturbance events. Historically large storms have a potential to cause power grid blackouts and transformer damage of unprecedented proportions, long-term blackouts, and lengthy restoration times, and chronic shortages for multiple years are possible. As Kappenman summed up, "An event that could incapacitate the network for a long time could be one of the largest natural disasters that we could face."

Solutions for the Future

Given the potentially enormous implications of power system threats due to space weather, major emphasis focuses on preventing storm-related catastrophic failure. Trends have been in place for several decades that have

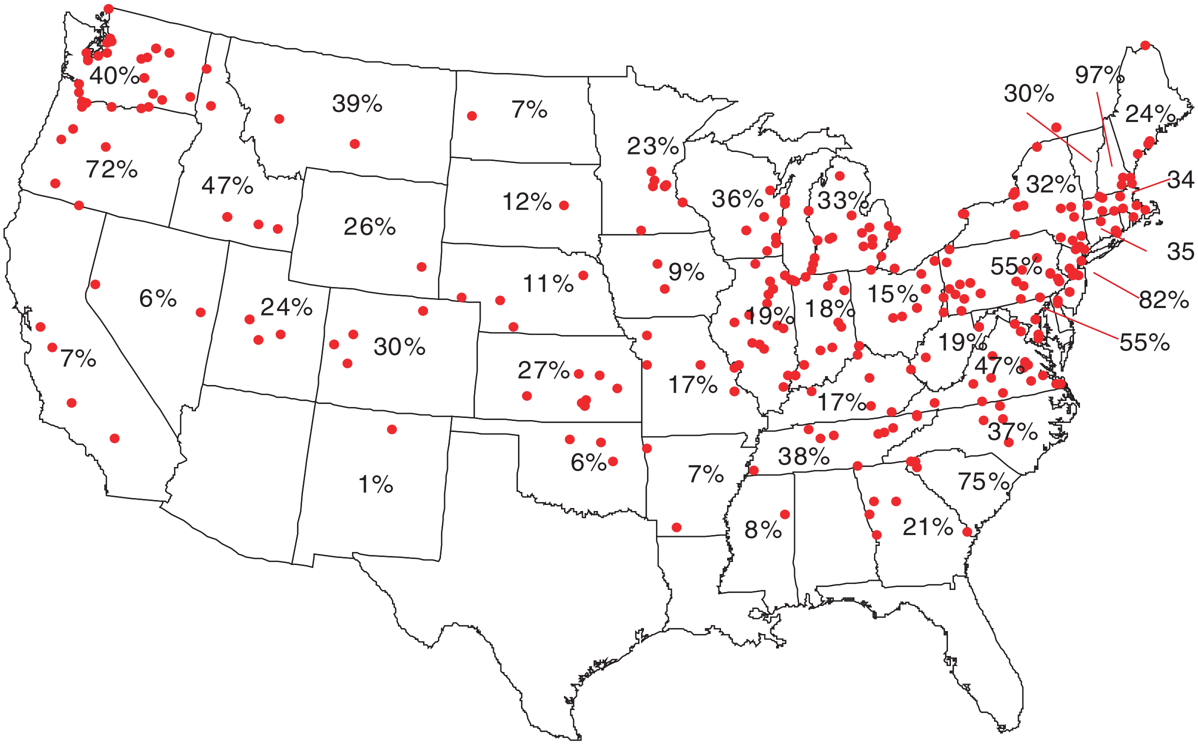

FIGURE 7.2 A map showing the at-risk EHV transformer capacity (estimated at ~365 large transformers) by state for a 4800 nT/min geomagnetic field disturbance at 50° geomagnetic latitude. Regions with high percentages of at-risk capacity could experience long-duration outages that could extend multiple years. SOURCE: J. Kappenman, Metatech Corp., "The Future: Solutions or Vulnerabilities?," presentation to the space weather workshop, May 23, 2008.

acted to inadvertently escalate the risks from space weather to this critical infrastructure. Kappenman stated that procedures based on K-index-style alerts provide very poor descriptions of the impulsive disturbance environments and lead to uncertainties about the adequacy and efficacy of operational procedures during large storms. He offered several solutions for the future. With respect to the entire grid, remedial measures to reduce GIC levels are needed and are cost-effective. The installation of supplemental transformer neutral ground resistors to reduce GIC flows is relatively inexpensive, has low engineering trade-offs, and can produce 60-70 percent reductions of GIC levels for storms of all sizes. Additional research work is already under way by the EMP Commission in this area. Kappenman noted that improved situational awareness for power grid operators is needed and is readily available (i.e., with an emphasis on disturbance environments/GIC levels instead of ambiguous K/G indices). In addition, regional system operators require initial and continuing training to understand their assigned roles and responsibilities in protecting the power system during solar events using new tools.

Economic and societal costs attributable to impacts of geomagnetic storms could be of unprecedented levels. For example, consider the following cost estimates:

- August 14, 2003, Northeast blackout: $4 billion to $10 billion,[3]
- Hurricane Katrina: $81 billion to $125 billion,[4,5]
- Future severe geomagnetic storm scenario: $1 trillion to $2 trillion in the first year, and
- Depending on damage, full recovery could take 4 to 10 years.[6]