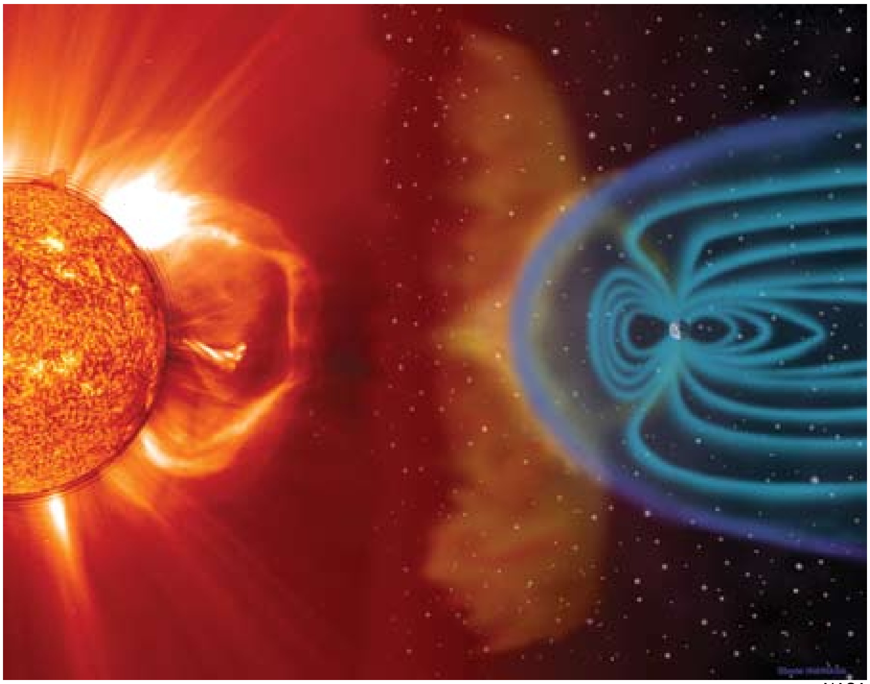

A coronal mass ejection (CME) blast and, at right, a depiction (not to scale) of the subsequent impact at Earth, two to four days later, when the CME cloud strikes and begins to be mostly deflected around the Earth's magnetosphere. The blue paths emanating from the Earth's poles represent some of its magnetic field lines. The magnetic cloud of plasma can extend to 30 million miles wide by the time it reaches Earth.

The Solar Storm Threat To America's Power Grid

by Laurence Hecht

A known and cataclysmic threat to the U.S. electric power grid is being largely ignored by the President and Congress. Warning events in 1859, 1921, 1989, and 2003 showed the danger that solar activity can pose to electrical power and distribution systems. Now, as we move into another solar maximum, with increased vulnerabilities built into our electrical grid, the danger again looms large. In the worst case, there is the possibility of no electricity for 130 million Americans for a year or longer. The warnings have been issued, but have gone unheeded.

The greatest danger is to the more than 300 extra-high-voltage (EVH) transformers located at power substations along the routes of major transmission lines. An eruptive event on the Sun, known as a coronal mass ejection (CME), sends a powerful flux of charged particles, protons and electrons, into the surrounding space. If the Earth is on a line with the eruption, the charged particles interact with the Earth's radiation belts and geomagnetic field to produce currents in the ionosphere. The power lines which make up the electrical transmission grid act as antennae, to couple these ionospheric currents to the installed transformers which step up the voltage for long-distance transmission.

High-voltage transmission lines in Washington state. Higher voltage lines are more susceptible to geomagnetic storm damage.

The ionospheric or auroral currents produced by a powerful solar storm induce strong fluctuating direct currents in the power lines. Known as geomagnetically induced currents (GIC), when they reach the transformers, they piggyback on to the strong alternating current already flowing, and cause the iron cores of the transformers to saturate and overheat from hysteresis and reactive resonance effects in the transmission line. This can cause network-wide voltage regulation problems leading to blackouts, or complete transformer burnout.

Transformer Failure

The consequences of a transformer failure are catastrophic, as there is a lack of manufacturing capacity for extra high-voltage transformers in the U.S.A. and worldwide. According to a study by the Metatech Corporation, commissioned under Executive Order 13407 for assessment of vulnerability to geomagnetic storms, manufacturers presently have a backlog of nearly three years for all extra high-voltage transformers (230 kilovolts and above).

Only one plant exists in the U.S.A. capable of manufacturing a transformer up to 345 kV. There is no manufacturing capability in the U.S.A. for 500 kV and 765 kV transformers, which represent the largest group of at-risk transformers in the U.S. power grid. The 500 and 765 kV transformers are the backbone of the grid that extends into regions that contain nearly 80 percent of the U.S. population,

Courtesy of J. Kappenman, Metatech Corp.

Transformer damage at Salem Nuclear Plant in New Jersey from overcurrent and stray flux heating during the 1989 geomagnetic storm.

according to John Kappenman of Storm Analysis Consultants and Metatech Corp.

Thus, as summarized by space physicist Daniel N. Baker, who chaired the National Research Council panel on Severe Space Weather Events, and NASA director of Planetary Sciences James L. Green, writing in the February 2011 *Sky & Telescope*: "Large areas of our nation could be without electricity for *months or years*, as power companies struggle to purchase and replace damaged hardware."

Because the solar storm threat is greatest to the low-resistance power lines carrying the highest current densities, some of the most vulnerable areas are also those of highest population concentration. Metatech estimates that more than 130 million people in the U.S.A. are at high risk for such an event. The highest risk areas are the northern states from the Atlantic seaboard to the Mississippi; coastal states as far south as Georgia; and the northwestern states of Washington, Oregon, and Idaho.

A prolonged lack of electricity in any of these areas would reduce the population to Dark Age-like conditions. Drinking water supply would break down for lack of pumping, and sewage service would cease shortly thereafter. For lack of refrigeration, the food chain would collapse, and medical supplies would be lost. Fuel could not be pumped, and thus transportation would break down. Heating and air conditioning systems would cease functioning.

Communication would be crippled by the lack of electricity as well as from the direct damage to satellites and sensitive electronics which a solar storm produces—perhaps no Internet and no cell phones. Modern life would come to an end, and a population and economic infrastructure unprepared for a return to pre-electricity conditions could descend into chaos.

The Remedies

Three means of mitigating the threat of severe geomagnetic storms and electromagnetic pulse damage are available:

- Provisions for replacement equipment, including spare transformers, circuit breakers, etc.
- Low-ohmic, neutral-to-ground resistors to reduce induced current levels at the transformer.
- Blocking devices to prevent the flow of geomagnetically induced currents.

Some combination of all three measures is urgently required. Maintaining reserve transformers on site, especially near critical metropolitan bottlenecks, is a must. But this would require the restoration of EHV transformer manufacturing capability in the U.S.A. and worldwide. The present backlog in production makes this option not available for the short term.

Immediate installation of supplemental transformer-neutral ground resistors can produce a 60 to 70 percent reduction of geomagnetically induced currents for storms of all sizes, according to Metatech. The EMP (Electromagnetic Pulse) Commission, established by Congress in 2001, estimated the cost of hardening the U.S. power grid with this first level of defense at $150 million.

There also exist conceptual designs for blocking devices, to shut down direct current flows from geomagnetically induced currents, while permitting normal AC flow on the power line. In one such design by Advanced Fusion Systems of New York, known as a Neutral Capacitor Bypass Device (NCBD), a high-power electron tube known as a Bi-Tron™ is utilized for fast bypass of induced currents, within a fraction of an alternating current cycle. The design envisions a modification and scaling of the 4275 Bi-Tron™ tube, originally developed for high-power military microwave applications, which has significantly faster switching capability than power transistors.

Without these measures, the power grid remains vulnerable to a catastrophic failure. Although satellites can provide warning of impending hits to Earth from solar coronal mass ejections, there are no viable options if preventive equipment and replacement transformers are not in place. Shutting down what might be thought to be the most vulnerable points in the grid, increases the risk of transformer saturation at other points by increasing the flow of power, in addition to the human and economic cost of a partial blackout in some areas.

Also, as noted by Metatech, the expansion of renewable energy greatly increases the threat posed by solar storms.

NASA

Technicians check the GOES-M satellite before its launch. GOES-M provides weather imagery and quantitative sounding data used to support weather forecasting, severe storm tracking, and meteorological research. It is one of a system of satellites that needs to be maintained if we are to have advance warning of superstorms.

To supply power from "wind farms," requires the construction of an extensive network of 765-kV transmission lines to bring the power from Midwestern states to the major metropolitan areas of the East and West coasts. "This could result in a seven-fold increase of the existing U.S. 765-kilovolt transmission network infrastructure," according to Kappenman, "and it would greatly escalate the vulnerability of the U.S. to geomagnetic storms, as higher voltage transformers are more vulnerable."

The Solar Storms

Solar coronal mass ejections, which produce the greatest known threat to Earth, are frequent but presently unpredictable events. The most powerful known storm occurred in 1859, at the beginning of the electrical age. It became known as the Carrington Event, after the British astronomer who observed "two patches of intensely bright and white light" from a group of sunspots near the center of the solar disk. The next day, a powerful geomagnetic storm occurred. American telegraph operators suffered damage to their equipment, and some reported a persisting signal on the line without any current being applied. Displays of Northern Lights were observed at low latitudes, lasting for a full week.

Another powerful geomagnetic superstorm was recorded in 1921. At that time, and up until the satellite era, the magnetic activity was associated with solar flares, which referred to the bright light observed in the eyepiece of a solar telescope. The magnetic effects could be detected by the global network of magnetic observatories, which dates back to the Göttingen Magnetic Union, founded by Carl Gauss and Wilhelm Weber in 1834.

The connection of geomagnetic storms to solar sunspot activity had been recognized since studies in the 1860s, after the Carrington event. But it was not until the 1970s that it was recognized that the coronal mass ejections, rather than the flare itself, were the cause of the geomagnetic storms. The solar flares are now recognized as intense eruptions from the Sun's visible surface, producing X-rays, radio emissions, and bursts of energetic particles, all of which can cause damage on Earth, and danger to humans in Earth orbit.

The 1991 eruption of Mt. Pinatubo was preceded for two weeks by some of the most intense X-class solar flares ever measured, although the causal connection of the events remains unknown. Since 1977, a continuous record of X-ray emission from solar flares has been re-

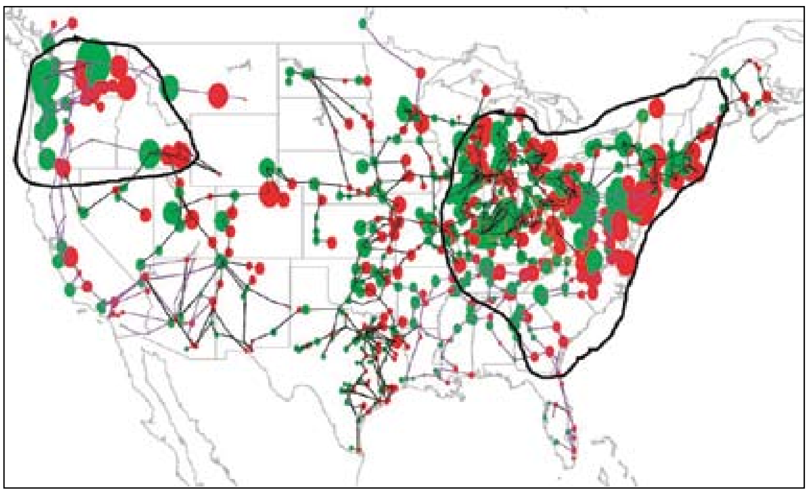

Figure 1
POSSIBLE EFFECTS OF A GEOMAGNETIC DISTURBANCE ON THE U.S. POWER GRID

The regions outlined are susceptible to system collapse, affecting more than 130 million people.

Source: J. Kappenman, Metatech Corp.

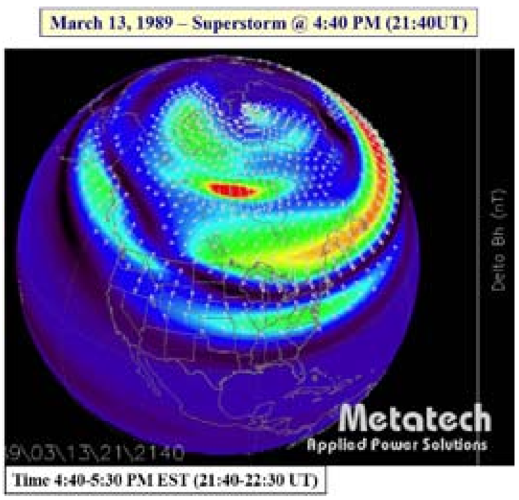

Figure 2

The geomagnetic superstorm, March 13, 1989, which caused a blackout in Quebec.

Source: J. Kappenman, Metatech Corp.

corded by the Earth-orbiting satellites of the GOES system.

Coronal mass ejections, which may or may not follow a solar flare, are eruptions of plasma, moving charged particles carrying with them a self-generated magnetic field, from the solar corona. A large coronal mass ejection can contain 10 billion tons or more of such material travelling at about 1 percent the speed of light. It is these charged particles, mostly protons and some electrons, which, when aimed at the Earth, produce the ionospheric currents which, in turn, can induce dangerous currents in the electric power grid.

Advanced Fusion Systems

The Bi-Tron™, devised by Advanced Fusion Systems of New York, is designed for fast bypass of induced currents, within a fraction of an alternating current cycle.

The Worst Recent Strike

The worst strike in modern times came on March 13, 1989, when currents induced by a coronal mass ejection tripped circuit breakers in the Hydro-Quebec network, leaving 6 million people without electricity for 9 hours to several days. Experts have described it as largely good fortune that a Northeast-wide power outage did not follow.

A more powerful CME accompanied by a solar flare occurred in November 2003, but was not aimed directly at Earth. According to experts, a direct hit by a CME of that magnitude would likely have produced a Carrington-level event, but with far worse consequences to a vastly more electricity-dependent planet. In that case, as in some others, the solar storm occurred, not in a period of peak activity, but during a solar minimum. However the threat of eruptive activity increases with the onset of the maximum in the 11-year cycle of solar activity. We are now approaching such a maximum in the current Solar Cycle 24, which commenced in December 2008.

Thanks to satellite systems, we now have sometimes up to a day or two of warning from the time the eruptive event is witnessed on the Sun's surface to the arrival of the charged particle flux which carries most of the known danger. But, as noted, it is not sufficient to know it is coming. Preventive devices and back-up equipment must be in place to avert a catastrophic consequence.

Remedies Not Taken

The warnings and required remedial measures reported here were delivered in repeated congressional testimony and compiled in a 2008 report by the National Academy of Sciences entitled, "Severe Space Weather Events—Understanding Societal and Economic Impacts." In the words of Dr. Baker, the chairman of the commission which produced the report, "It's difficult to fathom how damaging an 1859-type event might be in today's world." Yet, so far, no effective action has been taken to implement the necessary defenses.

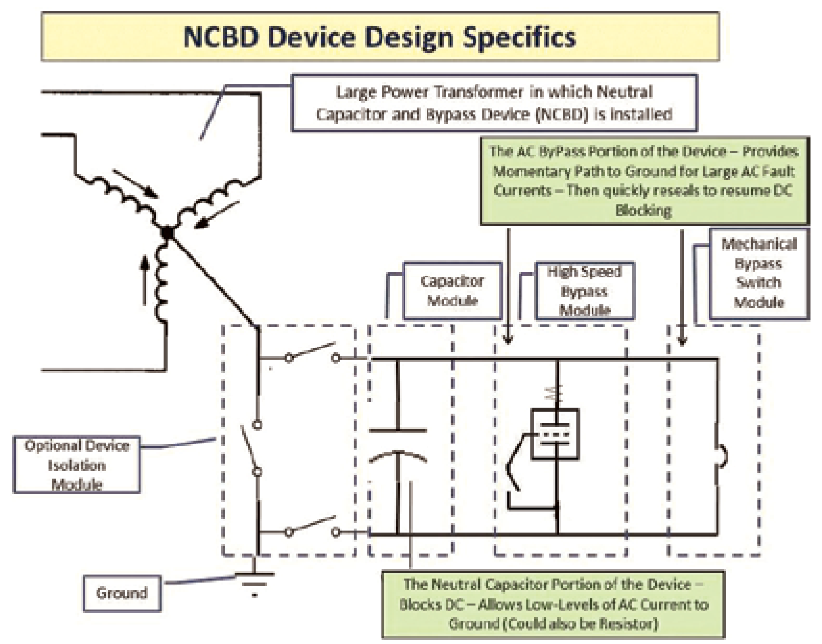

Figure 3

NEUTRAL CAPACITOR AND BYPASS DEVICE

Source: J. Kappenman, Metatech Corp.