
EMP
MANHATTAN
PROJECT
ORGANIZING SURVIVAL
AGAINST AN
ELECTROMAGNETIC PULSE (EMP)
CATASTROPHE

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"An EMP event causing a nationwide blackout lasting one year could kill 9 of 10 Americans by starvation, disease, and societal collapse."

Introducing Select New EMP Commission Reports

Dr. Peter Vincent Pry

EMP Task Force on National and Homeland Security

2018

EMP Task Force on National and Homeland Security

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An EMP Catastrophe

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This book is dedicated to
PRESIDENT DONALD TRUMP
For promising to protect electric grids and
other life-sustaining critical infrastructures in his new
National Security Strategy
And to
SENATOR RON JOHNSON
Chairman of the Senate Homeland Security Committee
For passage of the
Critical Infrastructure Protection Act

Many thanks to
Mr. James H. Hyde
For his heroic help publishing this book
And to
Mr. David Phelps
For designing the cover.

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INTRODUCTION

In 2008, when the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack delivered its over 100 recommendations to Congress to protect the national electric grid and other life-sustaining critical infrastructures—including communications, transportation, energy, business and finance, food and water—we were hopeful the job would get done.

After all, prior to the establishment of the EMP Commission, Congress spent a half-decade (1995-2000) educating themselves and the public in open hearings that a nuclear EMP attack, or natural EMP from a solar super-storm, poses a threat to national existence. Congress knew, prior to its establishment of the EMP Commission in 2001, from expert testimony that a manmade or natural EMP event could cause a protracted nationwide blackout.

326 million Americans cannot long survive bereft by EMP of the electronic civilization that sustains their lives. A nationwide blackout lasting one year could kill millions, perhaps prove fatal to most Americans, by starvation, disease, and societal collapse.

EMP is a civilization killer. Congress knew this before there was an EMP Commission.

The EMP Commission (2001-2008) conducted the most in depth and rigorous scientific analysis ever performed, including testing modern electronics in EMP simulators, proving the vulnerability of critical infrastructures necessary to national survival.

But the EMP Commission Reports are ultimately a “good news” story as they also prove there is no excuse for the nation to be vulnerable to EMP. The electric grid and other life-sustaining critical infrastructures can be protected, and at affordable cost.

Indeed, protected cheaply, relative to the cost of an EMP catastrophe.

For example, the 2008 EMP Commission Report estimates the electric grid bulk power system can be hardened to survive an EMP event for a few billion dollars, less than what the U.S. State Department gives away in foreign aid each year. And the cost of EMP protection for the national critical infrastructures need not be borne by federal taxpayers, but can be paid for through the utilities by electric power consumers modest rate increases.

So in 2008, when the EMP Commission delivered what we thought then was our final report to Congress, we were hopeful that our recommendations would be enacted and the American people protected from the existential threat that is EMP. By 2008, Congress and its EMP Commission had spent 13 years worrying about the threat—and 8 years developing good solutions.

However, by 2015—twenty (20) years after the first open congressional EMP hearing in 1995—the U.S. Government Accountability Office testified to Congress that their study found not a single major recommendation of the EMP Commission had yet been implemented. Not one.

Consequently, Congress re-established the EMP Commission for about two years (2015-2017) to re-examine the threat and make further recommendations.

The EMP Commission concludes in its new reports, some of which are appended to this book, that the threat to electric grids and other life-sustaining critical infrastructures is just as great, or greater, than in 2008. U.S. military power, the national economy, and civil society are increasingly dependent upon electricity and particularly electronics that are vulnerable to EMP.

And now North Korea has nuclear missiles and satellites that could make an EMP attack on the United States.

Moreover, on July 23, 2012, a massive and energetic coronal mass ejection crossed the orbit of the Earth, narrowly missing our planet by a few days. Thus, a repeat of the 1859 Carrington Event was avoided, which could have collapsed electric grids worldwide, and put at risk the lives of billions.

NASA now estimates the likelihood of a solar superstorm, of worldwide magnitude like the Carrington Event, is 12 percent per decade.

But perhaps the most alarming conclusion of the new EMP Commission Reports is that the U.S. Government—the Department of Defense, the Department of Homeland Security, the Department of Energy, the U.S. Federal Energy Regulatory Commission and the Nuclear Regulatory Commission—have proven themselves incapable of protecting our electronic civilization from EMP extinction.

The EMP Commissioners with whom I served for sixteen years are mostly from a generation accustomed to thinking of the U.S. Government as having the wisdom, vision, and competence to successfully accomplish great enterprises in the national interest and protect our nation from existential threats:

For example, during World War II, the U.S. Government transformed its almost non-existent U.S. Army (comprising 100,000 men, half of them without rifles) and technologically primitive armed forces into the liberators of Europe and Asia and the "Arsenal of Democracy" that defeated the formidable war machines of Nazi Germany and Imperial Japan.

For example, the World War II Manhattan Project (1942-1945), under the relentless administrative leadership of General Lesley Groves and scientific leadership of Robert Oppenheimer, invented the atomic bomb and built the scientific-industrial infrastructure that later produced thousands of A-Bombs and H-Bombs, and sustained the nuclear deterrent that preserved peace and won the Cold War.

For example, in 1954, with the launch of the USS Nautilus, Admiral Hyman Rickover began the construction of the so-called U.S. Nuclear Navy that soon included nuclear-powered aircraft carriers, cruisers, attack and ballistic missile submarines—this last the backbone of the U.S. nuclear deterrent. According to one Rickover biography "for three decades Rickover exercised tight control over the ships, technology, and personnel of the nuclear navy, even interviewing every prospective officer for new nuclear-powered navy vessels."

For example, the "1956 Dwight D. Eisenhower National System of Interstate and Defense Highways" (PL-84-627), under the personal leadership and supervision of President Eisenhower, launched construction of the world's largest highway system, 50,000 road miles costing $120 billion, for commercial and defense purposes, including evacuation of cities in the event of thermonuclear war.

For example, in 1958, President Eisenhower's "National Aeronautics and Space Act" created NASA, responding to the USSR's launch of a satellite causing the "Sputnik Crisis" (October 4, 1957). Under the driving scientific leadership of Werhner von Braun, at a peak cost to the federal budget of 4 percent (or about $20 billion annually in today's dollars) NASA sent Men to the Moon in 1969 and won the Space Race.

Whatever happened to the U.S. Government that was capable of such feats?

Compared to the above great enterprises and technological miracles, protecting our electronic civilization from EMP is easy to do. If the U.S. Federal Energy Regulatory Commission (FERC) passed a regulation requiring the utilities to protect the electric grid from 100 kilovolts/meter E1 EMP and 85 volts/kilometer E3 EMP, the problem would be addressed seriously and eventually solved.

Significantly, the electric utilities and all the life-sustaining critical infrastructures already are well-protected against lightning, a natural form of EMP (equivalent to E2 EMP), because there are regulations and engineering standards that require such protection. So the system worked once, even proved itself capable of protecting against a form of EMP, but works no longer.

Bureaucratic politics, which is another way of saying deliberate negligence and gross incompetence, accounts for why the U.S. Government has failed to protect the American people from the existential threat that is EMP. For example:

--U.S. FERC is a rotating door for lawyers and lobbyists serving electric utilities and has been "captured" by the North American Electric Reliability Corporation (NERC), which is essentially a lobby for the electric power industry.

--The Department of Defense over-classifies data on the EMP threat and hardening techniques needed by electric utilities and private sector to protect the critical infrastructures, indifferent to the fact that DoD cannot defend the nation without electricity from the national grids.

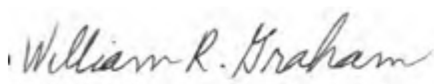
--The Department of Homeland Security, bereft of data on the real EMP threat from DoD, relies for EMP expertise on novices working for the Department of Energy.

--The Department of Energy relies for EMP expertise on novices and bureaucrats (one of whom has a degree from the University of Pennsylvania in ceramics), and on erroneous "junk science" studies by the Obama Administration and the Electric Power Research Institute, which is funded by NERC and the electric power industry.

--Despite President Trump's direction to the U.S. Government in his new National Security Strategy that the nation's electric grid and other life-sustaining critical infrastructures be protected from EMP, and despite Congress in the Critical Infrastructure Protection Act ordering protection of the nation from EMP as a legal obligation, bureaucrats in DHS and DOE deliberately ignore or dismiss the guidance of the President, the Congress, and the EMP Commission.

The bureaucratic Gordian knot preventing national EMP preparedness appears to be a greater challenge than winning World War II, the invention of the atomic bomb, the development of the nuclear navy, building the national highway system, or sending Men to the Moon.

What is needed is an EMP Manhattan Project—the subject of this book.



Dr. William R. Graham
Chairman
Commission to Assess the Threat to the United States from
Electromagnetic Pulse (EMP) Attack (2001-2017)
August 9, 2018

In 2001 Dr. William R. Graham was named Chairman of the Congressionally-mandated EMP Commission. He had previously served as President Ronald Reagan's Science Advisor and Director of the White House Office of Science and Technology Policy after serving as the Deputy Administrator of NASA. As an Air Force officer in the early 1960s he was a member of the defense science team that discovered the high altitude EMP phenomenon produced by the 1962 STARFISH PRIME nuclear test, and has subsequently played a leading role in testing and protecting U.S. strategic military systems from EMP since 1963.

EMP MANHATTAN PROJECT
Lessons From Building The Atomic Bomb
For Achieving
National EMP Preparedness

Dr. Peter Vincent Pry

The Manhattan Project (1942-1945) was a crash emergency program to develop the atomic bomb before Nazi Germany could do so, and confront Western Civilization with an unanswerable existential threat. Miraculously, in merely three years, the Manhattan Project organized an army of scientists and engineers, built nuclear industrial facilities and entire cities that never before existed, and achieved the seemingly impossible feat of translating arcane and problematical scientific theories into the reality of revolutionary new weapons that ended World War II and prevented the Cold War from becoming World War III.

Scholars will argue endlessly over whether the invention of the atomic bomb is a blessing or curse for Mankind. But incontrovertibly, the Manhattan Project is an example and paradigm of perhaps the most successful project in history harnessing science in the service of the national interest.

Today the United States and the world faces another existential threat—from an electromagnetic pulse (EMP) catastrophe, that can be caused by nature or Man, and topple the technological pillars of modern electronic civilization.

This report proposes another Manhattan Project to protect the U.S. electric grid and other life-sustaining critical infrastructures.

Why does the EMP threat warrant another Manhattan Project?

Appended are some of the most recent unclassified reports of the congressionally mandated Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack (also known as the Congressional EMP Commission) that provides the most definitive assessment of the EMP threat and solutions for purposes of public policy.

The Congressional EMP Commission Chairman, Dr. William Graham, warns that an EMP event causing a nationwide blackout lasting one year could kill up to 90 percent of the American people through starvation, disease, and societal collapse. An EMP catastrophe could, figuratively and literally, turn out the lights across entire nations and be the advent of a New Dark Ages.

Worth quoting at length is the Congressional EMP Commission's 2017 Executive Summary **Assessing the Threat from Electromagnetic Pulse (EMP)**:

The United States—and modern civilization more generally—faces a present and continuing existential threat from naturally occurring and manmade electromagnetic pulse assault and related attacks on military and critical national infrastructures. A nationwide blackout of the electric power grid and grid-dependent critical infrastructures—communications, transportation, sanitation, food and water supply—could plausibly last a year or longer. Many of the systems designed to provide renewable, stand-alone power in case of an emergency, such as generators, *uninterruptable power supplies (UPS), and renewable energy grid components, are also vulnerable to EMP attack.*

A long-term outage owing to EMP could disable most critical supply chains, leaving the U.S. population living in conditions similar to centuries past, prior to the advent of electric power. In the 1800s, the U.S. population was less than 60 million, and those people had many skills and assets necessary for survival without today's infrastructure. An extended blackout today could result in the death of a large fraction of the American people through the effects of societal collapse, disease, and starvation. While national planning and preparation for such events could help mitigate the damage, few such actions are currently underway or even being contemplated.

Combined-arms cyber warfare, as described in the military doctrines of Russia, China, North Korea, and Iran, may use combinations of cyber-, sabotage-, and ultimately nuclear EMP attack to impair the United States quickly and decisively by blacking-out large portions of its electric grid and other critical infrastructures. Foreign adversaries may aptly consider nuclear EMP attack a weapon that can gravely damage the U.S. by striking at its technological Achilles Heel, without having to confront the U.S. military. The synergism of such combined arms is described in the military doctrines of all these potential adversaries as the greatest revolution in military affairs in history—one which projects rendering obsolete many, if not all, traditional instruments of military power.

Any of several threats, as described here, must be considered:

--Solar superstorms can generate natural EMP over remarkably wide areas. Recurrence of the Carrington Event of 1859 is considered by many to be inevitable. NASA estimates the likelihood of such an event to be 10 to 12 percent per decade, making it very likely that Earth will be affected by a solar superstorm within a matter of decades. Such an event could blackout electric grids and other life-sustaining critical infrastructures, putting at risk the lives of many millions.

--Nuclear EMP attack might be conducted with only a single nuclear weapon detonated at high altitude or a few weapons at several hundred kilometers. These could be delivered by satellite, by a wide variety of long- and short-range missiles, including cruise and anti-ship missiles, by a jet doing a zoom-climb, or even by a high-altitude balloon. Some modes of attack could be executed relatively anonymously, thereby impairing deterrence.

--Russia, China, and North Korea now have the capability to conduct a nuclear EMP attack against the U.S. All have practiced or described contingency plans to do so. Terrorists or other less-sophisticated actors also might mount a nuclear EMP attack if they have access to a suitable nuclear explosive. For missile delivery, no re-entry system or accurate missile guidance would be necessary.

--Cyber-attack, using computer viruses and related means, might be able to blackout much of the national electric grid for extended intervals. According to U.S. Cyber Command, Russia and China

currently have such capability and it may only be a matter of time before other adversaries also gain a similar capability.

--The U.S. electrical grid could be sabotaged by damaging extra-high-voltage (EHV) transformers using rifles, explosives, or non-nuclear EMP or directed energy weapons. Attacking less than a dozen key substations could result in protracted and widespread blackouts, according to the public statements of a past Chairman of the U.S. Federal Energy Regulatory Commission (FERC). At least one substantive rehearsal of such an attack may have already taken place, at the Metcalf substation in the San Francisco Bay area.

The Congressional EMP Commission recommends protecting the national electric grid and other critical infrastructures utilizing wherever possible an “all hazards” strategy. Thus, protecting against the worst threat—nuclear EMP attack—can also mitigate all lesser threats, including natural EMP from a solar super-storm, non-nuclear EMP radiofrequency weapons, cyber-attacks, sabotage, and even severe weather like hurricanes.

The challenge of protecting the nation’s critical infrastructures from EMP is—from a scientific, technological, and financial perspective—modest compared to the original Manhattan Project. For example:

Scientifically, the original Manhattan Project began merely with a physics theory about atomic weapons, not knowing whether they would be possible or practical to build given the technology of the 1940s. In contrast, EMP is a proven scientific phenomenon demonstrated and well understood from:

--U.S. and Russian high-altitude nuclear tests;
--Decades of underground nuclear testing (yield and gamma ray output tells much about the EMP capabilities of a weapon);
--Over 50 years of testing on EMP simulators;
--The effects of non-nuclear EMP radiofrequency weapons, and;
--The effects of natural EMP generated by solar storms.

Technologically, the original Manhattan Project had to invent not only the atomic bomb, but a wide array of new machines, new chemical and metallurgical industries, new electronics and instruments, to manufacture and refine weapons-grade uranium and plutonium, U-235 and Pu-239 themselves being new materials that never before existed in more than microscopic quantities. In contrast, technologies for protecting electric grids and other life-sustaining critical infrastructures from EMP already exist and have been used to protect military systems for over a half-century. For example:
--Faraday Cages were invented in the 19th Century and have been adapted to protect key elements of military command and control, including Air Force One and the NORAD command post inside Cheyenne Mountain;

--Surge Arrestors against the full spectrum of EMP threats protect missiles, aircraft, satellites, communications and intelligence networks;
--Blocking Devices of various kinds already exist to protect against the powerful low-frequency E3 EMP generated by high-yield nuclear weapons and solar super-storms;
--New technologies for improved EMP protection at lower cost are continuously being invented and marketed.

Financially, the original Manhattan Project cost about $20 billion in today's dollars, an enormous expense for the U.S. Government in the midst of fighting World War II. In contrast, the Congressional EMP Commission estimates protecting the national electric grid would cost about $2 billion dollars, a relatively trivial expense, what the U.S. State Department used to spend on foreign aid to Pakistan every year (until President Trump canceled this undeserved largess to Islamabad).
--There are many ways and many plans for protecting electric grids from EMP and other threats, ranging from $200 million to $1 trillion, the latter envisioning replacement of the existing grid with a modern system of hardened regional microgrids connected by buried direct current (DC) cables that would eventually pay for itself through cheaper energy;
--For about $200 million the 400 most important Extra-High Voltage transformers serving the major metropolitan areas could be protected, significantly improving the security of the big cities;
--For $20 billion all of the life-sustaining critical infrastructures could be made significantly more survivable to an EMP and lesser threats;
--Funding EMP protection of the civilian critical infrastructures, that are mostly privately owned, need not cost federal dollars, but could be painlessly financed by modest service increases passed on to consumers;
--Since EMP hardening typically adds only 1-6% to product manufacturing costs, regulations requiring EMP protection as part of critical electronic systems design would, at very low cost, eventually result in an EMP protected society. EMP protection could become a benefit we take for granted, much as we now take for granted that critical systems are protected against lightning, which is a form of EMP.

So if EMP protection of the national electric grid and other life-sustaining critical infrastructures is—scientifically, technologically, and financially—much easier, even trivial, compared to the original Manhattan Project that invented the atomic bomb: then why is an EMP Manhattan Project necessary?

The bureaucratic politics of EMP protection have proven such a formidable obstacle that, despite the best bipartisan efforts of Congress, no real progress has been achieved implementing the EMP Commission's recommendations to protect the national critical infrastructures made in 2008, a decade ago. Despite a decade of educational and legislative effort, American civilization remains unprotected from EMP extinction.

And the U.S. Government of the 21st Century is not the same highly competent U.S. Government of the Great Generation that successfully ran the Manhattan Project to invent the atomic bomb, won World War II, built the national highway system, and sent Man to the Moon. Today's U.S. Government is not competent to make a website for Obamacare, spends $500 million to train a Free Syrian Army of 50 men who mostly defect to Al Qaeda, relies on Russia to send U.S. astronauts into orbit, and is generally so corrupt, incompetent, and obstructionist that it seems no longer capable of carrying out great enterprises, as it did in the past.

An EMP Manhattan Project is necessary because the bureaucratic politics of EMP protection may be an even more formidable obstacle than the scientific, technological, and financial obstacles that faced the original Manhattan Project's invention of the atomic bomb.

It is worth quoting at length again from the Congressional EMP Commission's 2017 Executive Summary providing an example of the bureaucratic politics that has for so long roadblocked national preparedness to survive an EMP catastrophe:

The government's response to the EMP Commission recommendations made in 2008 is not encouraging.

In a 2011 study, the DoD's JASON advisory panel concluded that the federal response to the EMP risk "is poorly organized; no one is in charge, resulting in duplications and omissions between agencies."

A survey of recent government reports that address the protection of critical infrastructure reveals that none mention EMP, although critical infrastructure risks, resilience, protection, and availability are central to each report and to each Departments' mission.

During a hearing before the Senate Homeland Security and Government Affairs (SHSGA) Committee on July 22, 2015, the U.S. Government Accountability Office (GAO) acknowledged that none of the recommendations of the EMP Commission to protect the national grid from EMP have been implemented by DHS, DOE, U.S. FERC or the North American Electric Reliability Corporation (NERC). The GAO report explained lack of progress in protecting the national electric grid from EMP as due to a lack of leadership, because no one was in charge of solving the EMP problem, as follows: "DHS and DOE, in conjunction with industry, have not established a coordinated approach to identifying and implementing key risk management activities to address EMP risks."

In March 2016, GAO reported that none of the essential measures recommended by the EMP Commission to protect the national electric grid had been addressed by Federal agencies, as shown in Table 1. The report stated that agencies had primarily drafted industry standards and federal guidelines and have only completed related research reports rather than implementing the resulting recommendations.

Table 1: Status of Previous Recommendations from the EMP Commission

Recommendation	*Action*
Expand and extend emergency power supplies	*None*
Extend black start capability	*None*
Prioritize and protect critical nodes	*None*
Expand and assure intelligent islanding capability	*None*
Assure protection of high-value generation assets	*None*
Assure protection of high-value transmission assets	*None*
Assure sufficient numbers of adequately trained recovery personnel	*None*

Some efforts have been made, but these have been frustrated by a lack of leadership. For example, in October 2016, President Obama issued a comprehensive Executive Order for coordinating efforts to prepare the nation for space weather events. The primary federal mechanism for coordination is the interagency Space Weather Operations, Research, and Mitigation (SWORM) task force. This Executive Order gave DHS overall leadership in geomagnetic disturbance preparedness and the DOE leadership in addressing grid impacts, yet neither department has yet done a credible job of preparing the U.S. for such storms. This minimal effort did not address preparing the nation for similar wide-area effects on the electric power grid caused by an EMP attack.

Despite advocacy for a combined standard to protect the U.S. bulk power system from both man-made EMP and natural occurring solar storms, FERC in May 2013 ordered development of operating procedures and hardware protection standards only for solar geomagnetic disturbances. Upon recommendations of the designated Electric Reliability Organization, NERC, FERC issued guidance for operational procedures to cope with solar storms in FERC Order 779.20 These procedures excluded owner-operator requirements to protect generating facilities with generator step-up transformers, even those that have experienced transformer fires and explosions in prior solar storms. After development of a benchmark model by a NERC Geomagnetic Disturbance Task Force, in September 2016 FERC issued a standard for phased assessments of potential hardware protections that utilities would perform over a period ofyears, but without any mandatory hardware-protection installations actually required.

These scattered, incoherent, and inadequate responses are a clear indication that for at least the last decade, critical national infrastructure protection from EMP has been largely ignored or dismissed by major departments of the U.S. government. The unaddressed vulnerability of the U.S. to EMP is an incentive for hostile powers to attack or, at a minimum, to develop capabilities for HEMP attack.

The above is why an EMP Manhattan Project is necessary.

Lessons learned from the original Manhattan Project are that critical to the success of an EMP Manhattan Project will be three elements:

--Leadership
--Inventiveness
--Pressure

And of these the most important will be leadership.

Leadership
The EMP Commission recommends that an Executive Agent appointed by the White House be put in charge of captaining the advancement of national EMP preparedness with power, authority, and resources to cut through bureaucratic opposition:

The single most important action that requires immediate action to advance U.S. security and survivability is that the President establish an Executive Agent with the authority, accountability, and resources to manage U.S. national infrastructure protection and defense against the existential EMP threat (Recommendation 1). Current institutional authorities and responsibilities—government, industry, regulatory agencies—are fragmented, incomplete, under-resourced, and unable to protect and defend against foreign hostile EMP threats or solar superstorms.

During the original Manhattan Project, the Executive Agent assigned by the White House with the "authority, accountability, and resources" to invent the atomic bomb was Colonel Leslie Groves—promoted to General Leslie Groves to enhance his authority.

General Groves, a professional engineer serving in the U.S. Army Corps of Engineers, had a proven track record accomplishing seemingly impossible projects on schedule or ahead of time. Groves had just completed building the Pentagon in 3 years (1941-1943)—then one of the largest buildings in the world, of unique architectural design—before being assigned as the Executive Agent for the Manhattan Project.

The Executive Agent for the EMP Manhattan Project need not be a scientific EMP expert—just as General Groves was not an atomic physicist—but must have sufficient technical grasp to guide his strategic planning and bureaucratic battling for resources and to make rapid progress.

General Groves was a consummate "street fighter" in bureaucratic battles, indefatigable, ruthless, and domineering. These "virtues" propelled the Manhattan Project forward through all the many bureaucratic obstacles and over the defeated bodies of competing project managers, to achieve a revolution in science and warfare in merely three years.

Kenneth Nichols, a member of the Manhattan Project, in his book **The Road To Trinity** (1987) describes General Groves' characteristics that made him a successful Executive Agent in unflattering, but ultimately appreciative, terms:

First, General Groves is the biggest S.O.B. I have ever worked for. He is most demanding. He is most critical. He is always a driver, never a praiser. He is abrasive and sarcastic. He disregards all normal organizational channels. He is extremely intelligent. He has the guts to make difficult, timely decisions. He is the most egotistical man I know. He knows he is right and so sticks by his decision. He abounds with energy and expects everyone to work as hard or even harder than he does. Although he gave me great responsibility and adequate authority to carry out his mission-type orders, he constantly meddled with my subordinates. However, to compensate for that he had a small staff, which meant that we were not subject to the usual staff-type heckling. He ruthlessly protected the overall project from other government agency interference, which made my task easier. He seldom accepted other agency cooperation and then only on his own terms. During the war and since I have had the opportunity to meet many of our most outstanding leaders in the Army, Navy and Air Force as well as many of our outstanding scientific, engineering and industrial leaders. And in summary, if I had to do my part of the atomic bomb project over again and had the privilege of picking my boss I would pick General Groves.

The Executive Agent of the EMP Manhattan Project must be so obsessively dedicated to protecting the nation from an EMP catastrophe that he must be willing to sacrifice his career in service of the cause, as General Groves did on behalf of the original Manhattan Project:

The Army Chief of Staff, General of the Army Dwight D. Eisenhower, met with Groves on 30 January 1948 to evaluate his performance. Eisenhower recounted a long list of complaints about Groves pertaining to his rudeness, arrogance, insensitivity, contempt for the rules and maneuvering for promotion out of turn. Eisenhower made it clear that Groves would never become Chief of Engineers. Groves realized that in the rapidly shrinking postwar military he would not be given any assignment similar in importance to the one he had held in the Manhattan Project, as such posts would go to combat commanders returning from overseas, and he decided to leave the Army….Groves went on to become a vice president at Sperry Rand, an equipment and electronics firm, and moved to Darien Connecticut, in 1948. (Robert Norris, **Racing for the Bomb: General Leslie R. Groves, the Manhattan Project's Indispensable Man**, 2002)

Inventiveness

Just as the original Manhattan Project had the best and brightest atomic physicists working on the team that actually invented the atomic bomb, the EMP Manhattan Project must have the best and brightest EMP scientific and technical experts and the best and brightest electrical engineers experienced in design, construction, and operations of electric grids and other life-sustaining critical infrastructures.

Inventiveness and technological daring by the best and brightest were key to ultimate successful invention of the atomic bomb.

For example, the original Manhattan Project invented and pursued simultaneously several competing industrial processes for making and refining enough uranium-235 and plutonium-239 for an atomic weapon. The original Manhattan Project also invented and pursued two competing designs for making an atomic bomb.

Consequently, in merely three years, by 1945, the Manhattan Project not only accomplished the "impossible mission" of making an atomic bomb—it built *two* atomic bombs of radically different design. One was a uranium-fueled gun-type bomb called *Little Boy* that destroyed Hiroshima. The other was a plutonium-fueled implosion bomb named *Fat Man* that destroyed Nagasaki.

Proven technologies already exist to protect against EMP. But an EMP Manhattan Project can and should test, evaluate, and if possible invent new technologies that can do the job better and cheaper.

New technologies for protecting against EMP are continuously coming on the market from independent inventors. At least some of these could be highly significant.

For example, the late great Bronius Cikotas, a member of the EMP Commission staff, invented an EMP filter for EHV transformers that could lower the cost of protection from $500,000 to $3,000 per transformer. Unfortunately, Bron passed away unexpectedly while undergoing hip surgery before his new invention could be turned into a prototype and tested.

Large-scale inventiveness protecting electric grids is made possible by the Critical Infrastructure Protection Act (CIPA). Senator Ron Johnson, Chairman of the Senate Homeland Security Committee, deserves vast credit for passage of CIPA as part of the 2016 National Defense Authorization Act. CIPA is now law of the land.

A very important CIPA provision requires the Department of Homeland Security to work with States and utilities on pilot projects to prove electric grids can be protected from EMP cost-effectively.

Thus, CIPA provides legal authority and DHS resources for an EMP Manhattan Project to conduct large-scale experimentation with EMP protection of entire State electric grids. Since there is more than one way to protect electric grids from EMP, CIPA provides an opportunity to have several competing programs in several different States to develop the most cost-effective solution for EMP protection.

Moreover, as the EMP threat is so proximate, the States selected for EMP protection pilot programs could be selected strategically to maximize protection for the nation as a whole.

For example, California has so much electrical generating capacity, and is such a large consumer of electricity, that EMP protection of this single state would do much to advance the energy security of the entire Western Grid. Pennsylvania has more EHV transformers than any other state, literally making it the "keystone state" in the architecture of the Eastern Grid.

Other States might be selected to be among the first for EMP protection based on the number or importance of their military bases, or other considerations that contribute to overall national security. For example, the Virginia electric grid sustains Washington, D.C., the locus of national government, as well as many important military bases, not least the U.S. Navy base at Norfolk. The Louisiana electric grid sustains Barksdale AFB, one of only three strategic bomber bases, while the state itself is a major national resource for energy and transportation via air, road, rail, and the Mississippi River.

Pressure
The original Manhattan Project was a pressure-cooker from fear that Nazi Germany might be first to develop and use the atomic bomb. General Groves never let members of his team forget the looming Nazi A-bomb threat, and used it relentlessly to flog his scientists to always do more, to work harder, to work longer, to be more creative.

When the Alsos intelligence program monitoring Nazi Germany's A-bomb project concluded Hitler was not near success, General Groves deliberately withheld this information from his people to keep the pressure on.

Unlike the phantom Nazi A-bomb, the EMP threat really is imminent.

As noted earlier, NASA estimates the likelihood of a natural EMP catastrophe is 12 percent per decade. We are overdue for another Carrington Event that could collapse electric grids and life-sustaining critical infrastructures worldwide, putting at risk the lives of billions.

Another Carrington Event could happen tomorrow.

Two North Korean satellites orbit over the United States that, the Congressional EMP Commission warns, could be armed for a surprise nuclear EMP attack. As Dr. Wiliam Graham, Chairman of the EMP Commission, testified in his official statement submitted to Congress on October 12, 2017:

A Super-EMP weapon could be relatively small and lightweight, and could fit inside North Korea's Kwangmyongsong-3 (KMS-3) and Kwangmyongsong-4 (KMS-4) satellites. These two satellites presently orbit over the United States, and over every other nation on Earth--demonstrating, or posing, a potential EMP threat against the entire world.

North Korea's KMS-3 and KMS-4 satellites were launched to the south on polar trajectories and passed over the United States on their first orbit. Pyongyang launched KMS-4 on February 7, 2017, shortly after its fourth illegal nuclear test on January 6, that began the present protracted nuclear crisis with North Korea.

The south polar trajectory of KMS-3 and KMS-4 evades U.S. Ballistic Missile Early Warning Radars and National Missile Defenses, resembling a Russian secret weapon developed during the Cold War, called the Fractional Orbital Bombardment System (FOBS) that would have used a nuclear-armed satellite to make a surprise EMP attack on the United States.

An EMP sword of Damocles literally hangs over the head of the American people.

Yet so far Washington has done nothing—a lethargy that contrasts startlingly with the Washington of the 1940s Manhattan Project that spared no effort or resource to protect civilization from a hypothetical Nazi atomic bomb. And remember, during most of the Manhattan Project, the atomic threat really was hypothetical—no one knew if the A-bomb would work.

In contrast, the EMP threat is not hypothetical, but proven and imminent.

Yet Washington does nothing. It remains to be seen if even the imperative of national survival can overcome the deadly lethargy of bureaucratic inertia.

An EMP Manhattan Project may be our only hope.

The Congressional EMP Commission Reports

Appended are some of the newest unclassified reports produced by the Congressional EMP Commission before its termination in September 2017. These select reports have been reviewed by the Department of Defense and approved for unclassified publication in 2018. All of the unclassified EMP Commission reports released by the Department of Defense so far can be found at www.firstempcommission.org

The Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack studied the EMP threat and labored to make recommendations to protect U.S. critical infrastructures for 17 years. The Congressional EMP Commission was the greatest body of expertise on EMP, nuclear weapons, cyber warfare, critical infrastructures, and problem-solving ever focused on this existential threat by the Free World.

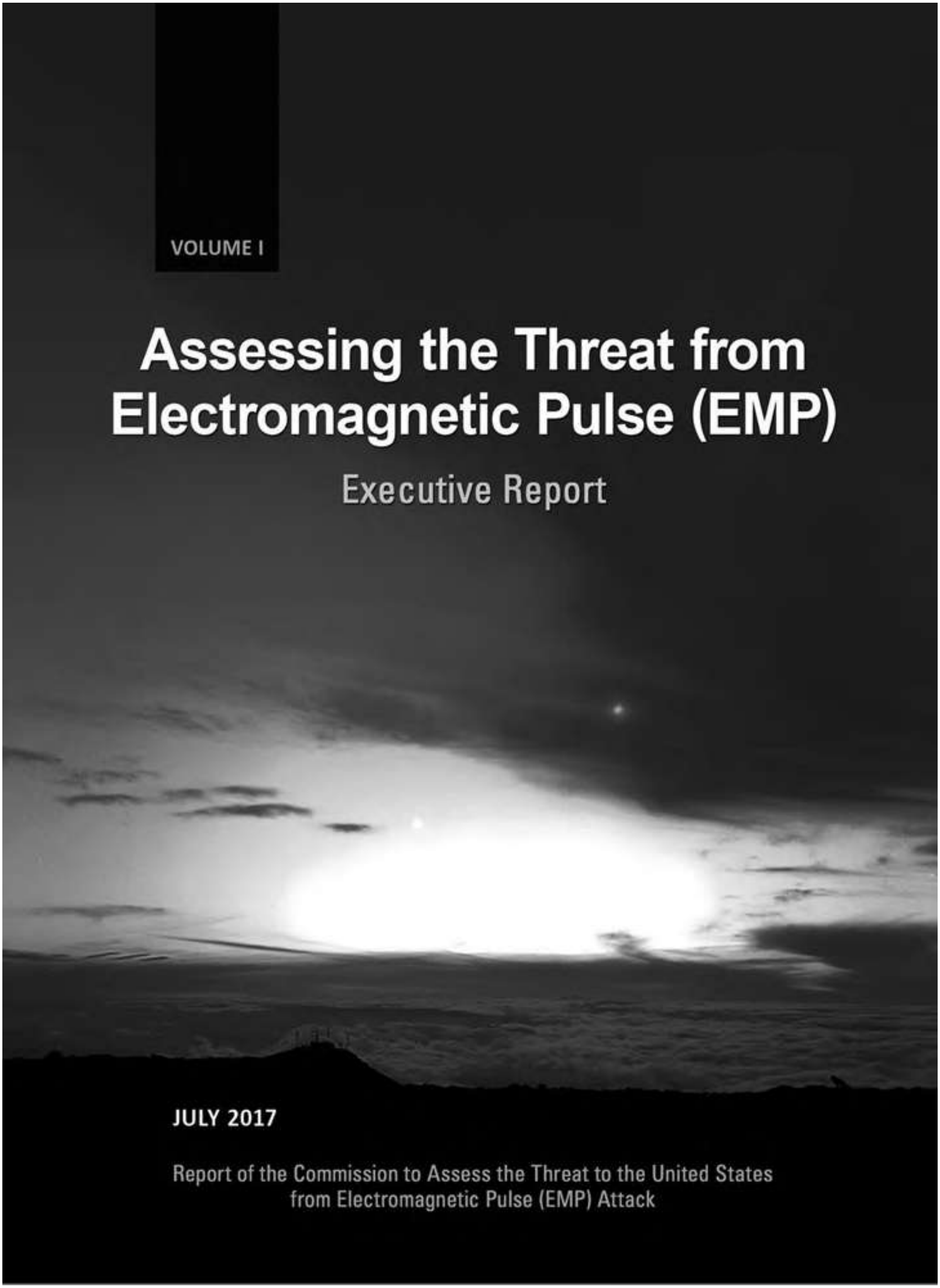
Therefore, the EMP Commission reports should be used as the baseline for the threat and for solutions. Collectively, the work of the Congressional EMP Commission constitutes a design for survival and the foundations for an EMP Manhattan Project.

NEW REPORTS

by the

COMMISSION TO ASSESS THE THREAT TO THE UNITED STATES FROM ELECTROMAGNETIC PULSE ATTACK

Charts, graphs, and illustrations in the above reports appended are shown in black and white, while the colorized originals may be found at www.firstempcommission.org



VOLUME I

Assessing the Threat from Electromagnetic Pulse (EMP)

Executive Report

JULY 2017

Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack

The cover photo depicts Fishbowl Starfish Prime at 0 to 15 seconds from Maui Station in July 1962, courtesy of Los Alamos National Laboratory.

This report is a product of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. The Commission was established by Congress in the FY2001 National Defense Authorization Act, Title XIV, and was continued per the FY2016 National Defense Authorization Act, Section 1089.

The Commission completed its information-gathering in June 2017. The report was cleared for open publication by the DoD Office of Prepublication and Security Review on April 9, 2018.

Assessing the Threat from Electromagnetic Pulse (EMP)

Executive Report

July 2017

REPORT OF THE COMMISSION TO ASSESS THE THREAT TO THE UNITED STATES FROM ELECTROMAGNETIC PULSE (EMP) ATTACK

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS

DHS	Department of Homeland Security
DoD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
ELECTRA	Electromagnetic Effects Comparison Test and Reliability Assessment
EMP	electromagnetic pulse
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FDA	Food and Drug Administration
FERC	Federal Energy Regulatory Commission
HEMP	high-altitude electromagnetic pulse
NERC	North American Electric Reliability Corporation
NRC	Nuclear Regulatory Commission

PREFACE

The Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack (herein and elsewhere referred to as "the EMP Commission") was re-established by the National Defense Authorization Act (NDAA) for Fiscal Year 2016 on November 25, 2015, and funded by the appropriation for the Commission on December 18, 2015. Delays by the Department of Defense in providing funding, clearance support, and contractor support to the Commission throughout 2016 delayed the first meeting until January 2017. The Commission's statutory mandate terminated at the end of June 2017 in accord with the terms of the NDAA. EMP is a complex subject, and the DoD provided only limited support beyond this time to allow the Commission to complete its work even though funding to continue was available. As a result, the Commission could not adequately complete the full scope of the Congressional charge as described in Appendix A. This report is therefore necessarily limited, yet the Commission is confident this material contained herein is accurate and trusts it is valuable to the recipients.

Following the last meeting of the EMP Commission on June 8-9, 2017, global events have strengthened public awareness of the worldwide vulnerability of critical infrastructures to high altitude EMP. North Korean state news, KCNA, displayed photos of an alleged thermonuclear weapon and claimed on September 3, 2017, "The H-bomb, the explosive power of which is adjustable from tens of kilotons to hundreds of kilotons, is a multi-functional thermonuclear nuke [sic] with great destructive power which can be detonated even at high altitudes for super-powerful EMP (electromagnetic pulse) attack according to strategic goals." The United States, its territories, and allies are therefore the target of current threats by the government of North Korea that specifically include EMP, and also include further development and exploitation of high altitude EMP weapons.

EXECUTIVE SUMMARY

The critical national infrastructure in the United States faces a present and continuing existential threat from combined-arms warfare, including cyber and manmade electromagnetic pulse (EMP) attack, as well as from natural EMP from a solar superstorm. During the Cold War, the U.S. was primarily concerned about an EMP attack generated by a high-altitude nuclear weapon as a tactic by which the Soviet Union could suppress the U.S. national command authority and the ability to respond to a nuclear attack—and thus negate the deterrence value of assured nuclear retaliation. Within the last decade, newly-armed adversaries, including North Korea, have been developing the ability and threatening to carry out an EMP attack against the United States. Such an attack would give countries that have only a small number of nuclear weapons the ability to cause widespread, long-lasting damage to critical national infrastructures, to the United States itself as a viable country, and to the survival of a majority of its population.

Major efforts have been undertaken by the Department of Defense to assure that the U.S. national command authority and U.S. strategic forces could survive and operate after an EMP attack. However, no major efforts were thought necessary to protect critical national infrastructures, relying on nuclear deterrence to protect them. With the development of small nuclear arsenals and long-range missiles by small, hostile, and potentially irrational adversaries, including North Korea, the threat of a nuclear EMP attack against the U.S. becomes one of the few ways that such a country could inflict devastating damage to the United States. It is critical, therefore, that the U.S. national leadership address the EMP threat as a critical and existential issue, and give a high priority to assuring the leadership is engaged and the necessary steps are taken to protect the country from EMP. Otherwise, foreign adversaries may reasonably consider such an attack as one which can gravely damage the U.S. by striking at its technological Achilles' heel without having to engage the U.S. military.

Protecting and defending the national electric grid and other critical infrastructures from cyber and EMP could be accomplished at reasonable cost and minimal disruption to the present systems that comprise U.S. critical infrastructure. This is commensurate with Trump Administration plans to repair and improve U.S. infrastructures, increase their reliability, and strengthen homeland defense and military capability. Continued failure to address the U.S. vulnerability to EMP generated by a high-altitude nuclear weapon invites such an attack.

The single most important action *that requires immediate action* to advance U.S. security and survivability is that the President establish an Executive Agent with the authority, accountability, and resources to manage U.S. national infrastructure protection and defense against the existential EMP threat (*Recommendation 1*). Current institutional authorities and responsibilities—government, industry, regulatory agencies—are fragmented, incomplete, under-resourced, and unable to protect and defend against foreign hostile EMP threats or solar superstorms.

The Commission highly commends President Trump's Executive Order 13800, *Strengthening the Cybersecurity of Federal Networks and Critical Infrastructure*, signed on May 11, 2017. **The Commission strongly recommends that implementation of cybersecurity for the electric grid and other critical infrastructures include EMP protection** *(Recommendation 2)*, because all-out cyber warfare may well include nuclear EMP attack. Protecting against nuclear EMP will also protect against natural EMP from solar storms, although the converse is not true. The United States must take steps to mitigate its current state of vulnerability to these well-known natural and adversary EMP threats. To further this endeavor, **the Commission encourages the President to work with Congressional leaders to establish a joint Presidential-Congressional Commission, with its members charged with supporting the Nation's leadership to achieve, on an accelerated basis, the protection of critical national infrastructures**. *(Recommendation 3).*

Across the U.S. government, the DoD and its supporting laboratories and contractors have by far the most knowledge, data, and experience related to the production of and survival from nuclear weapon-generated EMP. However, the DoD has largely failed to make this knowledge available to other government agencies and to the organizations that develop, build, and operate U.S. critical national infrastructure. For example, there has been a continuing unwillingness of the DoD to provide specific information about the EMP environment to the commercial community owing to classification restrictions. Today the DHS looks to the DOE to provide guidance and direction for protecting the national electric power grids. Such a course of action would take longer and cost more compared to establishing a program of cooperation with the knowledgeable parts of the DoD.

In the absence of an unclassified, well-informed U.S. late-time (E3) EMP threat specification [described in Appendix B], electric utilities, electrical equipment manufacturers, and electric research institutes have articulated their inability to design appropriate countermeasures and to justify cost recovery for capital investments programs. Accordingly, this Commission has prioritized the development of late-time E3 threat specifications, derived from openly available test data. As part of this assessment, Commission staff analyzed E3 EMP measurements from two nuclear high-altitude tests performed by the Soviet Union in 1962. Physicists with extensive experience in EMP modeling used these data waveforms and an understanding of the scaling relationships for the nuclear explosion-induced upper atmospheric heave phenomenon that produces the E3 EMP electromagnetic fields by disturbing the natural magnetic field of the Earth. Based on this analysis, **the Commission recommends that government agencies and industries adopt new standards to protect critical national infrastructures from damaging E3 EMP heave fields, with more realistic standards of 85 V/km** *(Recommendation 4).* Typical waveforms for commercial applications are included in Appendix B that should prove useful for the protection of the national power grids. **The Commission also recommends**

electric grid equipment with long-replacement times such as large power transformers be tested to system failure *(Recommendation 5).*

In the area of national intelligence, the Commission found that the classified report by the Joint Atomic Energy Intelligence Committee (JAEIC) on EMP issued in 2014 is factually erroneous and analytically unsound. **The Commission recommends the Director of National Intelligence circulate to all recipients of the 2014 JAEIC report the EMP Commission critique of that report and direct a new assessment be prepared that supersedes the 2014 JAEIC EMP report** *(Recommendation 6)*. The new report should be reviewed by experts in the subject areas being addressed and circulated to all the recipients of the 2014 assessment.

OBSERVATIONS, ANALYSIS, AND RECOMMENDATIONS

The Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack was previously convened by the Congress from 2001-2005 and from 2007-2008, and currently from 2016-2017.[1,2]

The current Commission assessment is consistent with the previous recommendations. In summary, the Commission sees the high-altitude nuclear explosion-generated electromagnetic pulse as an existential threat to the survival of the United States and its allies that can be exploited by major nuclear powers and small-scale nuclear weapon powers, including North Korea and non-state actors, such as nuclear-armed terrorists.

THE EMP THREAT

The United States—and modern civilization more generally—faces a present and continuing existential threat from naturally occurring and manmade electromagnetic pulse assault and related attacks on military and critical national infrastructures. A nationwide blackout of the electric power grid and grid-dependent critical infrastructures—communications, transportation, sanitation, food and water supply—could plausibly last a year or longer.[3] Many of the systems designed to provide renewable, stand-alone power in case of an emergency, such as generators, uninterruptable power supplies (UPS), and renewable energy grid components, are also vulnerable to EMP attack.[4]

A long-term outage owing to EMP could disable most critical supply chains, leaving the U.S. population living in conditions similar to centuries past, prior to the advent of electric power.[5] In the 1800s, the U.S. population was less than 60 million, and those people had many skills and assets necessary for survival without today's infrastructure. An extended blackout today could result in the death of a large fraction of the American people through the effects of societal collapse, disease, and starvation. While national planning and preparation for such events could help mitigate the damage, few such actions are currently underway or even being contemplated.

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1 The EMP Commission has previously published two unclassified reports: *Executive Report* dated 2004, and *Critical National Infrastructures*, dated 2008.

2 See Appendix A, "Legislation Re-establishing the Commission," National Defense Authorization Act for Fiscal Year 2016, Sec. 1089.

3 For example, see E. Conrad, G. Gurtman, G. Kweder, M. Mandell, and W. White. *Collateral Damage to Satellites from an EMP Attack,* Report to the EMP Commission, DTRA-IR-10.22.

4 Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. *HEMP Direct Drive Testing of Sample Solar Systems*. Report of the EMP Commission. July 2017.

5 National Security Telecommunications Advisory Committee (NSTAC). *People and Processes: Current State of Telecommunications and Electric Power*, January 31, 2006.

Combined-arms cyber warfare, as described in the military doctrines of Russia, China, North Korea, and Iran, may use combinations of cyber-, sabotage-, and ultimately nuclear EMP-attack to impair the United States quickly and decisively by blacking-out large portions of its electric grid and other critical infrastructures.[6] Foreign adversaries may aptly consider nuclear EMP attack a weapon that can gravely damage the U.S. by striking at its technological Achilles Heel, without having to confront the U.S. military. The synergism of such combined arms is described in the military doctrines of all these potential adversaries as the greatest revolution in military affairs in history—one which projects rendering obsolete many, if not all, traditional instruments of military power.

Any of several threats, as described here, must be considered:

- Solar superstorms can generate natural EMP over remarkably wide areas. Recurrence of the Carrington Event of 1859 is considered by many to be inevitable.[7] NASA estimates the likelihood of such an event to be 10 to 12 percent per decade, making it very likely that Earth will be affected by a solar superstorm within a matter of decades.[8] Such an event could blackout electric grids and other life-sustaining critical infrastructures, putting at risk the lives of many millions.
- Nuclear EMP attack might be conducted with only a single nuclear weapon detonated at high altitude or a few weapons at several hundred kilometers. These could be delivered by satellite, by a wide variety of long- and short-range missiles, including cruise and anti-ship missiles, by a jet doing a zoom-climb, or even by a high-altitude balloon. Some modes of attack could be executed relatively anonymously, thereby impairing deterrence.
- Russia, China, and North Korea now have the capability to conduct a nuclear EMP attack against the U.S. All have practiced or described contingency plans to do so.[9] Terrorists or other less-sophisticated actors also might mount a nuclear EMP attack if

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6 For example, see Army of the Islamic Republic of Iran, Passive Defense: Approach to the Threat Center (Tehran: Martyr Lt. General Sayad Shirazi Center for Education and Research, Spring 2010); Shen Weiguang, World War, the Third World War—Total Information Warfare; General Vladimir Slipchenko, Non-Contact Wars (Moscow: January 1, 2000) translated in FBIS CEP20001213000001; and comments on North Korean state news on 3 September 2017.

7 R.A. Lovett. "What if the biggest solar storm on record happened today?" National Geographic News, March 4, 2011.

8 P. Riley and J.J. Love, "Extreme geomagnetic storms: Probabilistic forecasts and their uncertainties," Space Weather, v. 15, Jan. 2017, pp. 53-64. The probability of an extreme geomagnetic storm on the scale of the Carrington event varies based on the type of distribution used in the analysis from 3 (lognormal) to 10 (power law) per decade; see also P. Riley, "On the probability of occurrence of extreme space weather," Space Weather, v. 10, Feb. 2012, pp. 2101-2114, which estimates 12 percent per decade.

9 For example, see Army of the Islamic Republic of Iran, Passive Defense: Approach to the Threat Center (Tehran: Martyr Lt. General Sayad Shirazi Center for Education and Research, Spring 2010); Shen Weiguang, World War, the Third World War—Total Information Warfare; General Vladimir Slipchenko, Non-Contact Wars (Moscow: January 1, 2000) translated in FBIS CEP20001213000001; and comments on North Korean state news on 3 September 2017.

they have access to a suitable nuclear explosive. For missile delivery, no re-entry system or accurate missile guidance would be necessary.

- Cyber-attack, using computer viruses and related means, might be able to blackout much of the national electric grid for extended intervals. According to U.S. Cyber Command, Russia and China currently have such capability and it may only be a matter of time before other adversaries also gain a similar capability.[10]
- The U.S. electrical grid could be sabotaged by damaging extra-high-voltage (EHV) transformers using rifles, explosives, or non-nuclear EMP or directed energy weapons. Attacking less than a dozen key substations could result in protracted and widespread blackouts, according to the public statements of a past Chairman of the U.S. Federal Energy Regulatory Commission (FERC).[11] At least one substantive rehearsal of such an attack may have already taken place, at the Metcalf substation in the San Francisco Bay area.[12]
- The Commission highly commends President Trump's Executive Order 13800, "Strengthening the Cybersecurity of Federal Networks and Critical Infrastructure" signed on May 11, 2017. Including the potential for EMP as part of a cyber-attack is prudent when the current vulnerability of the U.S. electrical grid and critical infrastructures is taken into account.

Recommendation 2: *The Commission strongly recommends that implementation of cybersecurity for the electric grid and other critical infrastructures include EMP protection.*

BARRIERS TO EFFECTIVE PROTECTION FROM EMP

The government's response to the EMP Commission recommendations made in 2008 is not encouraging.

In a 2011 study, the DoD's JASON advisory panel concluded that the federal response to the EMP risk "is poorly organized; no one is in charge, resulting in duplications and omissions between agencies."[13]

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10 Admiral Michael Rogers, Director, National Security Agency and Commander, U.S. Cyber Command. "Cybersecurity Threats: The Way Forward," Testimony, House Permanent Select Committee on Intelligence, Nov. 20, 2014.

11 R. Smith. "U.S. Risks National Blackout From Small-Scale Attack," Wall Street Journal, March 12, 2014; and R. Smith. "How America Could Go Dark," Wall Street Journal, July 14, 2016.

12 R. Smith. "Assault On California Power Station Raises Alarm On Potential For Terrorism," Wall Street Journal, February 5, 2014.

13 MITRE, 2011. Impacts of Severe Space Weather on the Electric Grid, MITRE, 2011, Report JSR-11-320.

A survey of recent government reports that address the protection of critical infrastructure reveals that none mention EMP, although critical infrastructure risks, resilience, protection, and availability are central to each report and to each Departments' mission.[14]

During a hearing before the Senate Homeland Security and Government Affairs (SHSGA) Committee on July 22, 2015, the U.S. Government Accountability Office (GAO) acknowledged that none of the recommendations of the EMP Commission to protect the national grid from EMP have been implemented by DHS, DOE, U.S. FERC or the North American Electric Reliability Corporation (NERC).[15] The GAO report explained lack of progress in protecting the national electric grid from EMP as due to a lack of leadership, because no one was in charge of solving the EMP problem, as follows: "DHS and DOE, in conjunction with industry, have not established a coordinated approach to identifying and implementing key risk management activities to address EMP risks."[16]

In March 2016, GAO reported that none of the essential measures recommended by the EMP Commission to protect the national electric grid had been addressed by Federal agencies, as shown in Table 1. The report stated that agencies had primarily drafted industry standards and federal guidelines and have only completed related research reports rather than implementing the resulting recommendations.[17]

Table 1: Status of Previous Recommendations from the EMP Commission

Recommendation	*Action*
Expand and extend emergency power supplies	None
Extend black start capability	None
Prioritize and protect critical nodes	None
Expand and assure intelligent islanding capability	None
Assure protection of high-value generation assets	None
Assure protection of high-value transmission assets	None
Assure sufficient numbers of adequately trained recovery personnel	None

Some efforts have been made, but these have been frustrated by a lack of leadership. For example, in October 2016, President Obama issued a comprehensive Executive Order for

14 These reports include ***Mitigation of Power Outage Risks for Department of Defense Facilities and Activities 2015***, ***National Infrastructure Protection Plan 2013: Partnering for Critical Infrastructure Security and Resilience*** (DHS), and ***U.S. Department of Energy Strategic Plan 2014-2018.***

15 The Nuclear Regulatory Commission could be added to the list of deficient government agencies in that it has failed to similarly protect the nuclear power reactors and spent fuel storage facilities for which they are responsible.

16 U.S. Senate Committee on Homeland Security and Governmental Affairs. Full committee hearing on "Protecting the Electric Grid from the Potential Threats of Solar Storms and Electromagnetic Pulse," held July 22, 2015.

17 Government Accountability Office. *Critical Infrastructure Protection: Federal Agencies Have Taken Actions To Address Electromagnetic Risks, But Opportunities Exist To Further Assess Risks And Strengthen Collaboration*, GAO-16-243, March 2016.

coordinating efforts to prepare the nation for space weather events.[18] The primary federal mechanism for coordination is the interagency Space Weather Operations, Research, and Mitigation (SWORM) task force. This Executive Order gave DHS overall leadership in geomagnetic disturbance preparedness and the DOE leadership in addressing grid impacts, yet neither department has yet done a credible job of preparing the U.S. for such storms. This minimal effort did not address preparing the nation for similar wide-area effects on the electric power grid caused by an EMP attack.

Despite advocacy for a combined standard to protect the U.S. bulk power system from both man-made EMP and natural occurring solar storms, FERC in May 2013 ordered development of operating procedures and hardware protection standards only for solar geomagnetic disturbances.[19] Upon recommendations of the designated Electric Reliability Organization, NERC, FERC issued guidance for operational procedures to cope with solar storms in FERC Order 779.[20] These procedures excluded owner-operator requirements to protect generating facilities with generator step-up transformers, even those that have experienced transformer fires and explosions in prior solar storms. After development of a benchmark model by a NERC Geomagnetic Disturbance Task Force, in September 2016 FERC issued a standard for phased assessments of potential hardware protections that utilities would perform over a period of years, but without any mandatory hardware-protection installations actually required. [21]

These scattered, incoherent, and inadequate responses are a clear indication that for at least the last decade, critical national infrastructure protection from EMP has been largely ignored or dismissed by major departments of the U.S. government. The unaddressed vulnerability of the U.S. to EMP is an incentive for hostile powers to attack or, at a minimum, to develop capabilities for HEMP attack.

Interagency Cooperation and Centralized Governance

The DoD has, since 1962, understood the data, phenomena, magnitude, and importance of high-altitude electromagnetic pulse (HEMP) effects, and has applied that knowledge to certain military systems.[22] However, DoD has not adequately transferred that knowledge to other agencies of the government and to organizations that provide critical national infrastructures, such as electrical power and communications utilities. This is surprising because

18 The White House. “Coordinating Efforts to Prepare the Nation for Space Weather Events,” Executive Order 13744, October 13, 2016.
19 FERC Order No. 779, Reliability Standards for Geomagnetic Disturbances, May 16, 2013.
20 FERC Order No. 797, Reliability Standard for Geomagnetic Disturbance Operations, June 19, 2014.
21 FERC Order No. 830, Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events, September 22, 2016. On the last full day of the Obama Administration, FERC denied four appeals for rehearing of Order 830, in FERC Order No. 830-A, January 19, 2017.
22 Operation Fishbowl in 1962 was the last high-altitude nuclear test series conducted by the U.S. military.

the DoD depends upon these same critical national infrastructures for domestic military operations as well as the security of the nation. To the contrary, the DoD has withheld public distribution of and has classified much of the data and technology that underlies protection against EMP even though potential adversaries of the U.S. are generally familiar with such technology. It is interesting to note that some of the most useful data available for predicting the electromagnetic fields produced by a nuclear explosion have been derived from data published by the former Soviet Union.[23]

In the absence of technology transfer and other support by the DoD to other agencies of the government and the industries supporting critical national infrastructures, the DHS depends upon the DOE, as their Sector-Specific Agency, to provide guidance and direction for protecting the national electric power grids.[24] The DOE relies on the National Laboratories under its sponsorship to provide such guidance and direction. While it is possible to conduct new testing and analysis required to generate the data, such a course of action would take longer and cost more compared to establishing a program of cooperation with the knowledgeable offices and laboratories in the DoD. A more efficient alternative is establishing a DoD policy that makes much of the defense-controlled data concerning EMP technology available to the government agencies and industry that support the U.S. critical national electric power infrastructure.

Regulatory Conflicts of Interest

The current institutional arrangements for protecting and improving the reliability of the electric grids and other critical infrastructures through the FERC and the NERC are not designed to address major national security threats to the electric power grids and other national critical infrastructures. Using FERC and NERC to achieve this level of national security has proven to be ineffectual. New institutional arrangements are needed to advance preparedness to guard against EMP and related threats to our critical national infrastructures.

The current U.S. power industry is largely self-regulated under FERC, NERC, Nuclear Regulatory Commission (NRC), and the electric power industry companies. The EMP Commission assesses that the existing regulatory framework for safeguarding the security and reliability of the electric power grid, which is based upon a partnership between the U.S. Government's FERC and the private non-profit NERC representing the utilities, is not set up to protect the U.S. against hostile EMP attack. For example, the standards for protecting the power grids from geomagnetic disturbances caused by solar storms prescribe threat levels

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23 One of the best references for understanding and protecting against EMP is a translation of a Soviet handbook, entitled, "The Physics of Nuclear Explosions," Ministry of Defense of the Russian Federation, Central Institute of Physics and Technology, Volumes 1 and 2, ISBN 5-02-015124-6, 1997.

24 See the DHS Energy Sector overview at https://www.dhs.gov/energy-sector

below those recorded during major storms of historical record.[25] In May 2013, FERC ordered entities in the bulk power system to develop reliability standards to protect against solar geomagnetic disturbances (GMD). Generator operators were excluded. Despite multiple requests for FERC to develop a joint reliability standard for grid protection from both EMP and GMD hazards, NERC has only proposed limited standards for solar storm protection.[26,27] This can be attributed to the industry's desire to minimize protection requirements.

In public testimony before Congress, FERC has stated that it lacks regulatory power to compel NERC and the electric power industry to protect the grid from natural and nuclear EMP and other threats.[28] Consider the contrast in regulatory authority of the U.S. Federal Energy Regulatory Commission and similar regulatory agencies in the U.S. Government:

- The NRC has regulatory power to compel the nuclear power industry to incorporate nuclear reactor design features to make nuclear power safe. (To date, however, the NRC has not incorporated EMP survival criteria into design regulations. Further, that Commission has not required that spare transformers or emergency diesel generators be certified to be EMP-protected.)
- The U.S. Federal Aviation Administration (FAA) has regulatory power to compel the airline industry to ground aircraft considered unsafe, to change aircraft operating procedures considered unsafe, and to make repairs or improvements to aircraft in order to protect the lives of airline passengers.
- The U.S. Department of Transportation (DOT) has regulatory power to compel the automobile industry to install on cars safety glass, seatbelts, and airbags in order to protect the lives of the driving public.
- The U.S. Food and Drug Administration (FDA) has power to regulate the quality of food and drugs, and can ban under criminal penalty the sale of products deemed by the FDA to be unsafe to the public.
- The U.S. Environmental Protection Agency (EPA) has power to regulate clean air, clean water, and hazardous materials deemed by the EPA to be unsafe to the public.

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25 J.G. Kappenman and W. Radasky, *Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields,* Report to the EMP Commission, July 28, 2017. See also Foundation for Resilient Societies, Comments Submitted on Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events, FERC Docket No. RM15-11-000, July 27, 2015; supplementary comments submitted August 10, 2015.

26 Requests for rehearing of Order No. 830 were filed by the Foundation for Resilient Societies, Edison Electric Institute, Center for Security Policy, and Jewish Institute for National Security Affairs. These were denied in Docket No. RM15-11-001, issued January 19, 2017.

27 U.S. Federal Energy Regulatory Commission. "Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events," Docket No. RM15-11-000; Order No. 830, issued January 21, 2016.

28 Testimony of Joseph McClelland, U.S. FERC's Director of the Office of Electric Reliability, before the Senate Committee on Energy and Natural Resources (July 17, 2012); T. Sanders, "FERC's McClelland Calls For Enhanced Authority On Cyber-Security" Washington Energy Report, July 20, 2012.

Unlike the NRC, FAA, DOT, FDA, EPA, and most other U.S. government regulatory agencies, FERC does not have legal authority to compel the industry it is charged to regulate to act in the public interest. The U.S. FERC even lacks legal power to direct the electric utilities to install devices to protect the grid.

Currently, U.S. FERC only has the power to require NERC to propose a standard to protect the grid. NERC Standards are approved, or rejected, or remanded for further consideration by its membership, which is largely made up of representatives from the electric power industry. Once NERC proposes a standard to FERC, FERC cannot modify the standard, but must either accept or reject the proposed standard. If FERC rejects the proposed standard, NERC goes back to the drawing board, and the process starts all over again, often resulting in long delays for implementation of standards.

The DOE Quadrennial Energy Review released in January 2017 recommended, "… in the area of cybersecurity, Congress should provide FERC with authority to modify NERC-proposed reliability standards—or to promulgate new standards directly—if it finds that expeditious action is needed to protect national security in the face of fast-developing new threats to the grid. This narrow expansion of FERC's authority would complement DOE's national security authorities related to grid-security emergencies affecting critical electric infrastructure and defense-critical electricity infrastructure…"[29]

It is notable that this proposal would limit additional FERC authority to strengthen a reliability standard or to promulgate a new standard "in the area of cybersecurity." Although EMP hazards were not explicitly included in the proposed supplemental FERC authorities, EMP could be included under the cyber threat rubric as it directly debilitates cyber electronicsystems.

Moreover, testifying before a House Energy and Commerce Subcommittee on February 1, 2017, the Chief Executive Officer of NERC expressed opposition to any Congressional grant of new FERC legislative authority to strengthen or directly promulgate any new grid reliability standard that NERC had not already proposed, thereby undermining the FERC's ability to protect the U.S. electric power grids from EMP attack.[30]

The geomagnetic disturbance standards proposed by the NERC, which the FERC has adopted to date, substantially underestimate the magnitude of historical and future geomagnetic disturbances. No standards for protecting the grid against nuclear or non-nuclear EMP weapons have been proposed or adopted.[31]

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29 U.S. Department of Energy, *Transforming the Nation's Electricity System: The Second Installment of the QER*, January 2017, pp. S-16 and 7-7.

30 G.W. Cauley, *Hearing on the Electricity Sector's Efforts to Respond to Cybersecurity Threats*, Testimony before the House Subcommittee on Energy, Energy and Commerce Committee, February 1, 2017.

31 Federal Energy Regulatory Commission (FERC) Order 779, *Final Rule on Reliability Standard for Geomagnetic Disturbances*, Reliability Standard EOP-010-1, June 25, 2014; FERC Order 830, *Transmission System Planned*

Recommendations to Improve Governance

The Commission's chief recommendation is made to address the critical leadership deficiency.

> ***Recommendation 1:*** *The Commission recommends the President establish an Executive Agent with the authority, accountability, and resources to manage U.S. national infrastructure protection and defense against the existential EMP threat.*

The 2017 Presidential initiative to repair and strengthen U.S. infrastructure, cyber security, homeland defense, and military capability presents a unique opportunity to include measures for EMP protection that could obviate the existential threats from solar superstorms and combined-arms cyber warfare.

A second recommendation in the area of governance is to ensure a whole-of-government approach to the challenge of EMP protection. A joint Presidential-Congressional Commission on critical infrastructure protection could engage the free world's preeminent experts on EMP and related threats to serve the interagency in a manner akin to other advisory Commissions. For example, between 1947 and 1974, the Atomic Energy Commission advised the administration on how to attain most quickly and most cost-effectively the protection essential to long-term national survival and well-being. Such a structure would help the U.S. move beyond the current state of vulnerability to well-understood natural and man-made EMP threats.

> ***Recommendation 3:*** *The Commission encourages the President to work with Congressional leaders to establish a joint Presidential-Congressional Commission, with its members charged with supporting the Nation's leadership to achieve, on an accelerated basis, the protection of critical national infrastructures.*

Protecting the national electric grid and other critical infrastructures from the most severe of these threats—nuclear EMP attack—could be done in ways that protect against or significantly mitigate some other threats. Extensively tested, performance-proven technologies for EMP hardening have been developed and used by the DoD to protect critical military systems for over 50 years, and can be affordably adapted to protect electric grids and other critical infrastructures, at low-cost relative to that of an EMP catastrophe.

For example, the EMP Commission estimated in its 2008 report, critical parts of the national electric grid could be protected for about $2 billion.

Performance for Geomagnetic Disturbance Events, Reliability Standard TPL-007-1, Sep. 22, 2016, and FERC Order 830-A, *Denying Rehearing (of Order 830)*, January 19, 2017.

The U.S. knowledge base on EMP threat levels and waveforms is adequate. Likewise, EMP protection engineering is mature such that system protection programs can proceed immediately, without the need for lengthy additional research. The Commission is concerned that DOE and the Electric Power Research Institute (EPRI) are pursuing lengthy research and development programs to redefine environments and determine EMP system effects that introduce unnecessary delays in actual implementation of grid protection. The Commission finds that diverting these resources to pilot demonstration programs to protect selected sectors of the electric power grid would better serve the intent to protect the U.S. electrical grid. A strategic plan, along with the leadership to implement it, is needed now.

LATE-TIME EMP FIELDS AND EFFECTS (E3)

Solar superstorms, more formally called coronal mass ejection events, produce fields similar to EMP E3 effects. A NASA analysis states that "historical aurora records suggest a return period of 50 years for Québec-level storms and 150 years for very extreme storms, such as the 1859 Carrington event."[32] A high-altitude nuclear EMP event would also include higher frequency E1 and E2 fields. An understanding of the range of fields produced is required to understand their effects and the threat to the electrical grid.

To study the impact of these types of electromagnetic fields on extended electrical and communications transmission lines associated with the critical infrastructures, utilities need upper-bound, open-source information for the late-time (E3) high-altitude electromagnetic pulse threat waveform and its ground pattern. This need arises because of the effect of very low frequency electric field component (E3) coupled to horizontal electrical conductors, such as power transmission lines, that induce large quasi-direct current in those lines. When the quasi-direct current travels through the windings of large transformers handling high levels of power, they shift the magnetic field operating point in the core of the transformers, causing the transformer to generate abnormal harmonic waveforms that neither the transformer nor the electrical power system are able to manage. This results in overheating and damage to the transformers. Therefore, it is important that an unclassified bounding-case E3 waveform be available to those working in the commercial power equipment development and operation sectors.

While the DoD has developed high-altitude EMP waveforms (E1, E2, and E3) for its purposes, these are classified and not available for commercial use. The DoD policy of keeping its E3 threat specifications classified, and therefore not available to designers and operators of the U.S. national power grids, is, in the view of the Commission, much more damaging to the protection of U.S. critical national electrical power infrastructure than its release would be helpful to U.S. adversaries. Some potential adversaries, including Russia, have collected some of the

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[32] T. Phillips. "Near Miss: The Solar Superstorm of July 2012." Science@NASA, July 23, 2014

best E3 data during their high altitude nuclear tests and therefore are already aware of the magnitude of the E3 fields. The withholding of E3 information is a DoD policy that is neither in the interest of U.S. national security and survival, nor in the interest of the DoD, because the DoD depends on commercial power for many of its activities.

In the absence of an unclassified, well-informed E3 specification, the Commission tasked experts to assess the openly available E3 HEMP measurements from two nuclear high-altitude tests performed by the Soviet Union in 1962. Using these data and an understanding of the scaling relationships for the E3 HEMP heave phenomenon, bounding waveforms for commercial applications were developed.

Because the measured quantities during these tests were the magnetic fields, it is possible for technologists familiar with electromagnetic theory to compute the E3 electric fields, using known ground conductivity profiles. Other ground conductivity profiles could lead to even higher fields, but some of these profiles do not cover a very large area of the Earth.

After computing the electric fields using the Soviet measurements, the results were scaled to account for the fact that the Soviet measurement locations were not at the optimum points on the ground to capture the maximum peak fields. This process determined that the scaled maximum peak E3 EMP heave field would have been 66 volts per kilometer (V/km) for the magnetic latitude of the Soviet tests.

The measured results were also evaluated for the E3 EMP heave field. This parameter increases for burst points closer to the geomagnetic equator, displaying inverse latitude behavior compared to solar GMD fields. This scaling increases the maximum peak electric field up to 85 V/km for locations in the southern continental United States, and 102 V/km for locations near the geomagnetic equator, such as Hawaii. The levels in Alaska would be lower, with a peak value of 38 V/km. While as noted these are not worst-case levels, they are reasonable upper-bound values useful in designing, evaluating, and operating bulk electrical power transmission systems and long-haul copper and fiber communication and data networks.[33]

> ***Recommendation 4:*** *The Commission recommends that government agencies and industries adopt new standards to protect critical national infrastructures from damaging E3 EMP heave fields, with more realistic standards of 85 V/km.*

Typical waveforms for commercial applications are included in Appendix B that should prove useful for the protection of the national power grids.

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33 Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. *Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures*. Report of the EMP Commission, July 2017.

TESTING SELECTED EMP-VULNERABLE FULL-SYSTEM EQUIPMENT TO FAILURE

Some equipment that is essential for operation of critical infrastructures may be more economically stockpiled and stored in EMP-shielded structures than redesigned to be EMP-hardened. Other equipment with long replacement times or uncertainty of availability after an EMP attack will require EMP-hardening against E1, E2 and E3 hazards. While modeling of EMP vulnerability and mitigation measures is desirable, there is no substitute for full system testing to failure to project the likely post-EMP attack operability or prompt recovery of critical infrastructure equipment.

The Defense Nuclear Agency and its successor Defense Special Weapons Agency sponsored an innovative EMP evaluation program called the Electromagnetic Effects Comparison Test and Reliability Assessment (ELECTRA) from 1992 to 1995. ELECTRA performed both pre-test expert assessments of EMP survivability and system tests to failure using actual threat-level illumination and current injection testing. The ELECTRA Technical Review Group compared sealed-envelope analytical predictions of system EMP effects against post-test system effects. [34] Key findings from ELECTRA are pertinent to development of reliable and cost-effective EMP equipment protection and recovery programs.

The ELECTRA forecasting and test assessment program demonstrated that EMP system effects were most pronounced for modern electronic systems having unprotected external power and signal lines.[35] Moreover, forecasts by EMP survivability experts of pass-fail testing outcomes were no better than random coin-tossing when assessing actual system failures. Predictions of whether or not EMP effects would occur were frequently wrong and predictions for EMP current and voltage stress were subject to large errors (up to +/- 30 dB). System failures were predicted when none occurred, and conversely, no failures were predicted in cases where effects did occur. Pre-test predictions often missed the location—box, component—of system failure. The ELECTRA Technical Review Group concluded that methods used to predict EMP effects in a specific system that are based primarily on analysis orlow-level testing are not reliable and recommended,

> *Where reliable [electromagnetic effects] predictions for specific systems are required, protections should be based on high-level functional-response tests performed on the specific systems of interest.*[36]

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[34] The ELECTRA Program's Technical Review Group's interim report of January 1995 includes a set of unclassified chapters on program methodology. See G.H. Baker, P. Castillo, C. McDonald, *et al.*, Electromagnetic Effects Comparison Test and Reliability Assessment (ELECTRA) Program: Executive Summary (U).

[35] ELECTRA Executive Summary (1995), p. iv.

[36] ELECTRA Executive Summary (1995), p. 49.

Further, where one or several complex system samples are subjected to high-level EMP injection testing, the test results can be prudently attributed to the larger population.[37] Thus, threat-level testing of even one sample is helpful to characterize the vulnerability and survivability of the larger set of systems. For large power transformers operating at 345 kV, 500 kV, and 765 kV voltages, for example, the DoD has the capability to transport EMP injection and diagnostic monitoring equipment to sites where these units are deployed. *In situ* testing to failure of exemplars of the major types of large power transformers under load would confirm whether specific types of large power transformers require EMP-protective equipment and enable new type transformer designs that resist EMP effects.

> ***Recommendation 5:*** *The Commission recommends that the Department of Defense and the Department of Energy provide expedited threat-level, full-system testing of large power transformers in wide use within the bulk electric system and share key findings with the electric utility industry.*

INTELLIGENCE COMMUNITY ASSESSMENT OF THE EMP THREAT

Finally, the Commission found that the classified report by the Joint Atomic Energy Intelligence Committee (JAEIC) on EMP issued in 2014 is factually erroneous and analytically unsound.[38] We recommend that the DNI circulate to all recipients of the 2014 JAEIC report the EMP Commission critique and direct a new assessment be prepared, reviewed by experts in the subject areas being addressed, and circulated to all the recipients of the 2014 assessment.

> ***Recommendation 6:*** *The Commission recommends the Director of National Intelligence circulate to all recipients of the 2014 JAEIC report the EMP Commission critique and direct a new assessment be prepared that supersedes the 2014 JAEIC EMP report.*

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37 ELECTRA Executive Summary (1995), p. ii

38 Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. *Assessment of the 2014 JAEIC Report on High-altitude EMP Threats,* Report of the EMP Commission, July 2017.

CONCLUSIONS

The critical national infrastructure in the United States faces a present and continuing existential threat from combined-arms warfare, including cyber and manmade electromagnetic pulse (EMP) attack, as well as from natural EMP from a solar superstorm. During the Cold War, major efforts were undertaken by the Department of Defense to assure that the U.S. national command authority and U.S. strategic forces could survive and operate after an EMP attack. However, no major efforts were then thought necessary to protect critical national infrastructures, relying on nuclear deterrence to protect them. With the development of small nuclear arsenals and long-range missiles by new, radical U.S. adversaries, the threat of a nuclear EMP attack against the U.S. becomes one of the few ways that such a country could inflict devastating damage to the United States. It is critical, therefore, that the U.S. national leadership address the EMP threat as a critical and existential issue, and give a high priority to assuring the leadership is engaged and the necessary steps are taken to protect the country from EMP.

Protecting and defending the national electric grid and other critical infrastructures from cyber and EMP could be accomplished at reasonable cost and minimal disruption to the present systems that comprise U.S. critical infrastructure. The following six recommendations are offered to accomplish this goal.

Recommendation 1: *The Commission recommends the President establish an Executive Agent with the authority, accountability, and resources to manage U.S. national infrastructure protection and defense against the existential EMP threat.*

Recommendation 2: *The Commission strongly recommends that implementation of cybersecurity for the electric grid and other critical infrastructures include EMP protection.*

Recommendation 3: *The Commission encourages the President to work with Congressional leaders to establish a joint Presidential-Congressional Commission, with its members charged with supporting the Nation's leadership to achieve, on an accelerated basis, the protection of critical national infrastructures.*

Recommendation 4: *The Commission recommends that government agencies and industries adopt new standards to protect critical national infrastructures from damaging E3 EMP heave fields, with more realistic standards of 85 V/km.*

Recommendation 5: *The Commission recommends that the Department of Defense and the Department of Energy provide expedited threat-level, full-system testing of large power transformers in wide use within the bulk electric system and share key findings with the electric utility industry.*

Recommendation 6: *The Commission recommends the Director of National Intelligence circulate to all recipients of the 2014 JAEIC report the EMP Commission critique and direct a new assessment be prepared that supersedes the 2014 JAEIC EM report.*

APPENDIX A Legislation Re-establishing the Commission

SEC. 1089. REESTABLISHMENT OF COMMISSION TO ASSESS THE THREAT TO THE UNITED STATES FROM ELECTROMAGNETIC PULSE ATTACK.

(a) REESTABLISHMENT.—The commission established pursuant to title XIV of the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001 (as enacted into law by Public Law 106–398; 114 Stat. 1654A–345), and reestablished pursuant to section 1052 of the National Defense Authorization Act for Fiscal Year 2006 (Public Law 109–163; 50 U.S.C. 2301 note), known as the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack, is hereby reestablished.

(b) MEMBERSHIP.—Service on the Commission is voluntary, and Commissioners may elect to terminate their service on the Commission. If a Commissioner is unwilling or unable to serve on the Commission, the Secretary of Defense, in consultation with the chairmen and ranking members of the Committees on Armed Services of the House of Representatives and the Senate, shall appoint a new member to fill that vacancy.

(c) COMMISSION CHARTER DEFINED.—In this section, the term "Commission charter" means title XIV of the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001 (as enacted into law by Public Law 106–398; 114 Stat. 1654A–345 et seq.), as amended by section 1052 of the National Defense Authorization Act for Fiscal Year 2006 (Public Law 109–163; 50 U.S.C. 2301 note) and section 1073 of the John Warner National Defense Act for Fiscal Year 2007 (Public Law 109–364; 120 Stat. 2403).

(d) EXPANDED PURPOSE.—Section 1401(b) of the Commission charter (114 Stat. 1654A–345) is amended by inserting before the period at the end the following: ", from non-nuclear EMP weapons, from natural EMP generated by geomagnetic storms, and from proposed uses in the military doctrines of potential adversaries of using EMP weapons in combination with other attack vectors.".

(e) DUTIES OF COMMISSION.—Section 1402 of the Commission charter (114 Stat. 1654A–346) is amended to read as follows:

"SEC. 1402. DUTIES OF COMMISSION.

"The Commission shall assess the following:

"(1) The vulnerability of electric-dependent military systems in the United States to a manmade or natural EMP event, giving special attention to the progress made by the Department of Defense, other Government departments and agencies of the United States, and entities of the private sector in taking steps to protect such systems from such an event.

"(2) The evolving current and future threat from state and non-state actors of a manmade EMP attack employing nuclear or non-nuclear weapons.

"(3) New technologies, operational procedures, and contingency planning that can protect electronics and military systems from the effects a manmade or natural EMP event.

"(4) Among the States, if State grids are protected against manmade or natural EMP, which States should receive highest priority for protecting critical defense assets.

"(5) The degree to which vulnerabilities of critical infrastructure systems create cascading vulnerabilities for military systems.".

(f) REPORT.—Section 1403 of the Commission charter (114 Stat. 1654A–345) is amended by striking "September 30, 2007" and inserting "June 30, 2017".

(g) TERMINATION.—Section 1049 of the Commission charter (114 Stat. 1654A–348) is amended by inserting before the period at the end the following: ", as amended by the National Defense Authorization Act for Fiscal Year 2016".

APPENDIX B High Altitude Nuclear Explosion-Generated Electromagnetic Effects

In the case of high altitude nuclear bursts, three main phenomena come into play, each with distinct associated system effects:

1. The first, a "prompt" EMP field, also referred to as E1, is created by gamma ray interaction with stratospheric air molecules. It peaks at tens of kilovolts per meter in a few nanoseconds, and lasts for a few hundred nanoseconds. E1's broad-band power spectrum (frequency content in the 10s to 100s of megahertz) enables it to couple to electrical and electronic systems in general, regardless of the length of their penetrating cables and antenna lines. Induced currents range into the 1000s of amperes. Exposed systems may be upset or permanently damaged.
2. The second component of the EMP field, referred to as E2, is produced by delayed gamma rays and neutron-induced currents, lasts from microseconds to milliseconds, and has a magnitude in the hundreds of volts per meter. Its spectral characteristics are similar to those of naturally occurring lightning.
3. The third component, late-time EMP, also referred to as magnetohydrodynamic (MHD) EMP or E3, is caused by the distortion of the earth's magnetic field lines due to the expanding nuclear fireball and rising of heated and ionized layers of the ionosphere. The change of the magnetic field at the earth's surface induces currents of 100s-1000s of amperes in long conducting lines (a few kilometers or greater) that damage components of the electric power grid itself as well as connected systems. Long-line communication systems are also affected, including copper as well as fiber-optic lines with repeaters. Transoceanic cables are a prime example of the latter.

Solar storm geomagnetic disturbance (GMD) effects are the result of large excursions in the flux levels of charged particles from the Sun and their interactions with the Earth's magnetic field and upper atmosphere. Perturbation of the Earth's magnetic field, similar to MHD EMP, can generate overvoltages in long-line systems over large regions of the earth's surface affecting electric power and communication transmission networks.

For each effect, directly-affected systems may be upset or permanently damaged. For unmanned systems and industrial control systems, upset effects can cascade to cause permanent damage to other connected systems. Wide-area electromagnetic system effects are challenging due to their near-simultaneous initial effects and cascading effects on a wide array of infrastructures. Infrastructure systems comprised of long-line conductor networks are the most vulnerable to both effects. Susceptible networks include the electric power grid, land-line communications, and interstate pipelines. Effects on these networks will cascade to most other infrastructures. Smaller, self-contained, self-powered infrastructure systems (e.g. hand-held radios and vehicles) are also directly vulnerable, but only to EMP (not GMD) and to a lesser degree than long-line networks.

BIOGRAPHIES

COMMISSIONERS

Dr. William R. Graham is Chairman of the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack. He was Chairman of the Board and Chief Executive Officer of National Security Research Inc. (NSR), a Washington-based company that conducts technical, operational, and policy research and analysis related to US national security. Previously he served as a member of several high-level study groups, including the Department of Defense Transformation Study Group, the Defense Science Board, the Commission to Assess United States National Security Space Management and Organization (the Rumsfeld Commission on Space), the Commission to Assess the Ballistic Missile Threat to the United States (also led by Hon. Donald Rumsfeld), and the National Academies' Board on Army Science and Technology. From 1986–89 Dr. Graham was the Director of the White House Office of Science and Technology Policy while he served concurrently as Science Advisor to President Reagan, Chairman of the Federal Joint Telecommunications Resources Board, and member of the Arms Control Experts Group. Before going to the White House, he served as the Deputy Administrator of NASA. For 11 years, he served as a member of the Board of Directors of the Watkins-Johnson Company.

Dr. John S. Foster, Jr. began his career at the Radio Research Laboratory of Harvard University in 1942 and then volunteered to be an advisor to the 15th Army Air Force on radar countermeasures in Italy. In 1952, Dr. Foster joined the Lawrence Livermore National Laboratory, designed nuclear weapons, became Director of that Laboratory, then in 1965 served as Director of Defense Research and Engineering for the Department of Defense until 1973. He joined TRW to work on energy programs and then served on the Board, retiring in 1988. He currently serves as a consultant to LLNL and an Advisor to STRATCOM SAG Panel. He has served on the Air Force Scientific Advisory Board, Army Scientific Advisory Panel, Ballistic Missile Defense Advisory Committee, and Advanced Research Projects Agency. From 1973 – 1990 he was a member of the President's Foreign Intelligence Advisory Panel. He served as Chairman of the Defense Science Board from 1990 to 1993. He served on the Congressional Commission on the Strategic Posture of the United States and on the Advisory Committee to the Director of DARPA.

Mr. Earl Gjelde, P.E., is the Managing Director and Chief Executive Officer of Summit Group International, Ltd.; Summit Energy Group, Ltd.; Summit Energy International 2000, LLC; and Summit Power NW, LLC, primary participants in the development of over 5,000 megawatts of natural gas fired electric and wind generating plants within the United States. He has also held a number of government posts, serving as President George Herbert Walker Bush's Under (now called Deputy) Secretary and Chief Operating Officer of the US Department of the Interior (1989) and as President Ronald Reagan's Under Secretary and Chief Operating Officer of the US Department of the Interior (1985–1988). While in the Reagan administration he served concurrently as Special Envoy to China (1987), Deputy Chief of Mission for the US-Japan Science and Technology Treaty (1987–1988), and Counselor for Policy to the Director of the National Critical Materials Council (1986–1988); the Counselor to the Secretary and Chief Operating Officer of the US Department of Energy (1982-1985); and Deputy Administrator, Chief Operating Officer, and Power Manager of the Bonneville Power Administration (19801982). Prior to 1980, he was a principal officer of the Bonneville Power Administration.

Dr. Robert J. Hermann is a senior partner of Global Technology Partners, LLC, a Boston-based investment firm that focuses on technology, defense aerospace, and related businesses worldwide. In 1998, Dr. Hermann retired from United Technologies Corporation, where he was Senior Vice President, Science and Technology. Prior to joining UTC in 1982, Dr. Hermann served 20 years with the National Security Agency with assignments in research and development, operations, and NATO. In 1977, he was appointed Principal Deputy Assistant Secretary of Defense for Communications, Command, Control, and Intelligence. In 1979, he was named Assistant Secretary of the Air Force for Research, Development, and Logistics and concurrently was Director of the National Reconnaissance Office.

Mr. Henry (Hank) M. Kluepfel served as Vice President for Corporate Development at SAIC, where he was the company's leading cyberspace security advisor to the President's National Security Telecommunications Advisory Committee (NSTAC) and the Network Reliability and Interoperability Council (NRIC). Mr. Kluepfel is widely recognized for his 30-plus years of experience in security technology research, design, tools, forensics, risk reduction, education, and awareness, and he is the author of industry's de facto standard security base guideline for the Signaling System Number 7(SS7) networks connecting and controlling the world's public telecommunications networks. In past affiliations with Telcordia Technologies (formerly Bellcore), AT&T, BellSouth and Bell Labs, he led industry efforts to protect, detect, contain, and mitigate electronic and physical intrusions and led the industry's understanding of the need to balance technical, legal, and policy-based countermeasures to the then emerging hacker threat. He has been recognized as a Certified Protection Professional by the American Society of Industrial Security and is a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE).

Gen Richard L. Lawson, USAF (Ret.), served as Chairman of Energy, Environment and Security Group, Ltd., and as President and CEO of the National Mining Association. He also served as Vice Chairman of the Atlantic Council of the U.S.; Chairman of the Energy Policy Committee of the US Energy Association; Chairman of the United States delegation to the World Mining Congress; and Chairman of the International Committee for Coal Research. Active duty positions included serving as Military Assistant to the President; Commander, 8th Air Force; Chief of Staff, Supreme Headquarters Allied Powers Europe; Director for Plans and Policy, Joint Chiefs of Staff; Deputy Director of Operations, Headquarters US Air Force; and Deputy Commander in Chief, US European Command.

Dr. Gordon K. Soper served as the Group Vice President of Defense Group Inc., responsible for broad direction of corporate goals relating to company support of government customers in areas of countering the proliferation of weapons of mass destruction, chemical/biological defense and domestic preparedness, treaty verification research, nuclear arms control and development of new business areas and growth of technical staff. He has also provided senior-level technical support on a range of task areas to the Defense Threat Reduction Agency (DTRA), the Chemical and Biological National Security Program of National Nuclear Security Administration, and the Counterproliferation and Chem/Bio Defense Office of the Office of the Secretary of Defense. Previously, Dr. Soper was Principal Deputy to the Assistant to the Secretary of Defense for Nuclear, Chemical and Biological Defense Programs (ATSD (NCB); Director, Office of Strategic and Theater Nuclear Forces Command, Control and Communications (C3) of the Office of the Assistant Secretary of Defense (C3I); and Associate Director for Engineering and Technology/Chief Scientist at the Defense Communications Agency.

Dr. Lowell L. Wood, Jr. is retired from a career-long position on the technical staff of Lawrence Livermore National Laboratory, operated by the University of California for the U.S. Department of Energy, and an extended term as a Research Fellow of the Hoover Institution at Stanford University. Since his retirement a decade ago, Dr. Wood has continued part-time technical consulting in the commercial sector and serving as an External Advisor of the Bill & Melinda Gates Foundation, the world's largest private charity, focusing his efforts on global health and development. Dr. Wood holds the distinction of being the most inventive American in history, holding more U.S. patents on new inventions than any other person, including Thomas Edison, the previous record-holder.

Dr. Joan Woodard was Executive Vice President and Deputy Director of Sandia National Laboratories, responsible for all of Sandia's programs, operations, staff, and facilities. She was also responsible for the laboratory's strategic planning. Previously, Dr. Woodard was Vice President of the Energy, Information and Infrastructure Technology Division, where her responsibilities included energy-related projects in fossil energy, solar, wind, geothermal, geosciences, fusion, nuclear power safety and severe accident analysis, and medical isotope processing; environment-related programs in remediation, nuclear waste management and repository certification, and waste minimization; information technology programs in information surety, command and control systems, and distributed information systems; and programs responsible for security of the transportation of nuclear weapons and special nuclear materials, and safety of commercial aviation. Over 80 percent of the programs included industrial or academic partners, and the nature of the work ranged from basic research to prototype systems evaluation.

SENIOR ADVISORS

Dr. George H. Baker is a Professor Emeritus at James Madison University, where he directed the JMU Institute for Infrastructure and Information Assurance. Previously, Dr. Baker led the Defense Nuclear Agency's Electromagnetic Pulse (EMP) program, directed the Defense Threat Reduction Agency's assessment arm, and served as a member of the Congressional EMP

Commission Staff. Dr. Baker holds an M.S. in Physics from University of Virginia, and a Ph.D. in Engineering Physics from the U.S. Air Force Institute of Technology. Currently, Dr. Baker is CEO of BAYCOR, LLC, and is Director of the Foundation for Resilient Societies.

Mr. William R. Harris is an international lawyer specializing in arms control, nuclear non-proliferation, energy policy, and continuity of government. He worked on Hot Line upgrades, creation of linked Nuclear Risk Reduction Centers, and was a co-drafter of arms limitation treaties in 1986-87, 1991, and 1993. Mr. Harris worked for the RAND Corporation and in a variety of assignments for the U.S. Government. Mr. Harris holds a B.A. from Harvard College and a J.D. from Harvard Law School. Mr. Harris serves as Secretary and attorney for the Foundation for Resilient Societies.

Dr. Peter Vincent Pry is a recognized expert on protection strategies for electromagnetic pulse (EMP) and related threats. In addition to his service for the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, he has served on the Congressional Strategic Posture Commission, as Executive Director of the U.S. Nuclear Strategy Forum and the Task Force on National and Homeland Security (both Congressional Advisory Boards); as Professional Staff on the House Armed Services Committee of the U.S. Congress, with portfolios in nuclear strategy, WMD, Russia, China, NATO, the Middle East, intelligence, and terrorism; as an Intelligence Officer with the Central Intelligence Agency; and as a Verification Analyst at the U.S. Arms Control and Disarmament Agency. Dr. Pry has written numerous books and articles on national security issues.

Dr. William A. Radasky is President and Managing Engineer at the Metatech Corporation. Metatech develops technically sound and innovative solutions to problems in all areas of electromagnetic environmental effects, including: electromagnetic interference and compatibility, geomagnetic storm assessments and protection, nuclear electromagnetic pulse prediction, assessments, protection and standardization, and intentional electromagnetic interference assessments, protection and standardization. Dr. Radasky has published over 400 technical papers, reports and articles dealing with electromagnetic interference (EMI) and protection. In 2004 he received the Lord Kelvin Award from the International Electrotechnical Commission for exceptional contributions to international standardization.

Dr. David Stoudt is a Senior Executive Advisor at Booz Allen where he provides leadership and guidance on the science and business of advancing directed energy capabilities for American warfighters. He previously spent 32 years serving in the Department of Navy, with deep experience in directed energy and electric weapon systems, including high-energy lasers, the electromagnetic rail gun, and high-power microwave weapon systems. Among other honors, David has received multiple Meritorious Civilian Service Awards, the Navy Distinguished and Superior Civilian Service Awards, and the Naval Sea Systems Command Scientist of the Year Award.

Ambassador R. James Woolsey Jr., J.D., is a national security and energy specialist and former Director of Central Intelligence who headed the Central Intelligence Agency from

February 5, 1993, until January 10, 1995. A lawyer by training and trade, he held a variety of government positions in the 1970s and 1980s, including as Under Secretary of the Navy from 1977 to 1979, and was involved in treaty negotiations with the Soviet Union for five years in the 1980s, including as Chief Negotiator of the Conventional Forces in Europe Treaty.

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Assessment of the 2014 JAEIC Report on High-altitude Electromagnetic Pulse (HEMP) Threats, **SECRET//RD-CNWDI//NOFORN**, 2017

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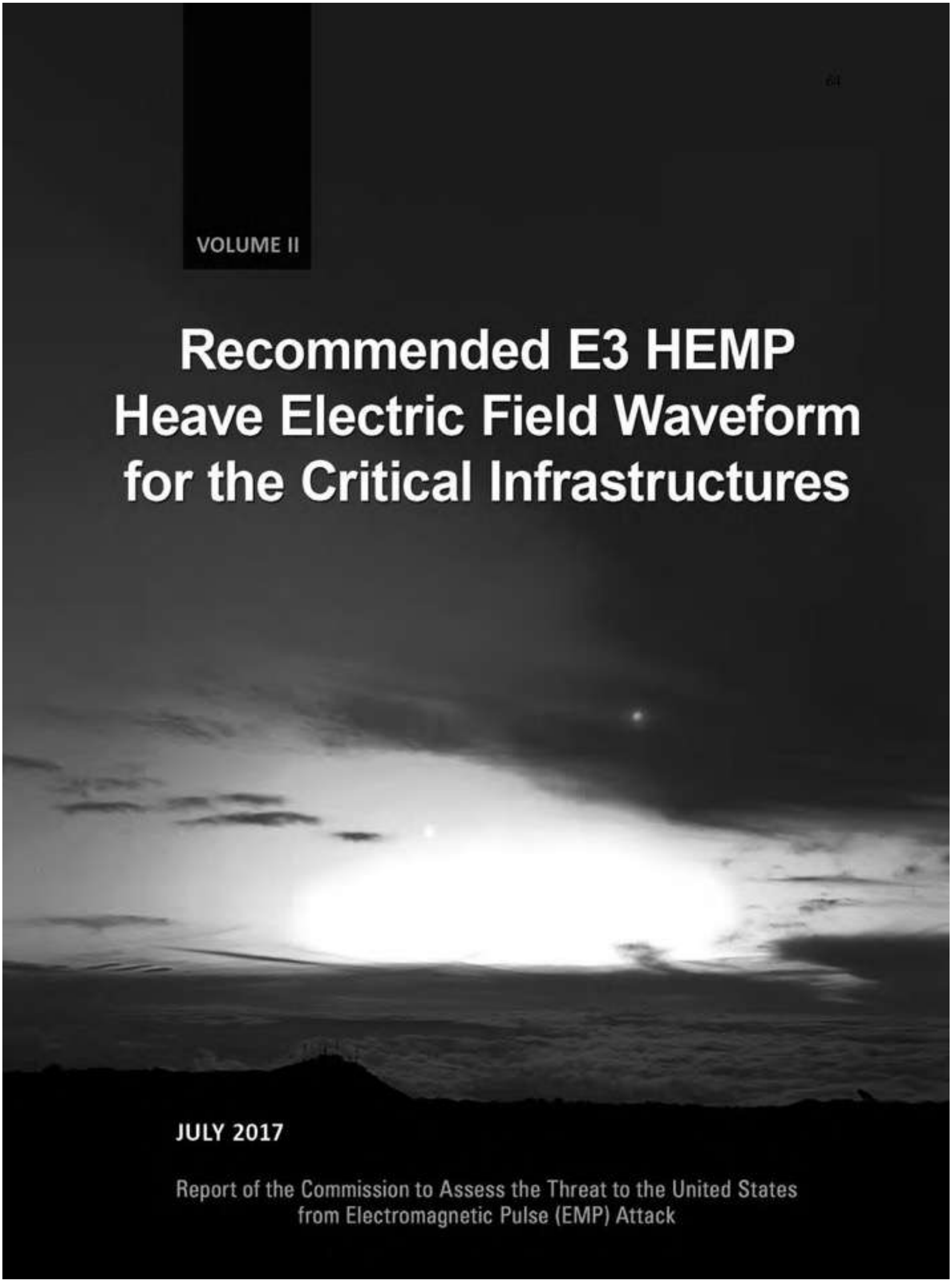

VOLUME II

Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures

JULY 2017

Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack

The cover photo depicts Fishbowl Starfish Prime at 0 to 15 seconds from Maui Station in July 1962, courtesy of Los Alamos National Laboratory.

This report is a product of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. The Commission was established by Congress in the FY2001 National Defense Authorization Act, Title XIV, and was continued per the FY2016 National Defense Authorization Act, Section 1089.

The Commission completed its information-gathering in June 2017. The report was cleared for open publication by the DoD Office of Prepublication and Security Review on April 9, 2018.

Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures

July 2017

REPORT OF THE COMMISSION TO ASSESS THE THREAT TO THE UNITED STATES FROM ELECTROMAGNETIC PULSE (EMP) ATTACK

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ACRONYMS AND ABBREVIATIONS

B	magnetic field
CONUS	continental United States
DoD	Department of Defense
E	electric field
EMP	electromagnetic pulse
EPRI	Electric Power Research Institute
FERC	Federal Energy Regulatory Commission
GMD	geomagnetic disturbance
HEMP	high-altitude electromagnetic pulse
HOB	height of burst
km	kilometer
m	meter
MHD	magnetohydrodynamic
min	minute
NERC	North American Electric Reliability Corporation
nT	nanotesla
S/m	siemens/m
UV	ultraviolet
V	Volt

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PREFACE

This EMP Commission Report, utilizing unclassified data from Soviet-era nuclear tests, establishes that recent estimates by the Electric Power Research Institute (EPRI) and others that the low-frequency component of nuclear high-altitude EMP (E3 HEMP) are too low by at least a factor of 3. Moreover, this assessment disproves another claim--often made by the U.S. Federal Energy Regulatory Commission (FERC), the North American Electric Reliability Corporation (NERC), EPRI and others—that the FERC-NERC Standard for solar storm protection against geo-magnetic disturbances (8 volts/kilometer, V/km) will also protect against nuclear E3 HEMP. A realistic unclassified peak level for E3 HEMP would be 85 V/km for CONUS as described in this report. New studies by EPRI and others are unnecessary since the Department of Defense has invested decades producing accurate assessments of the EMP threat environment and of technologies and techniques for cost-effective protection against EMP. The best solution is for DoD to share this information with industry to support near-term protection of electric grids and other national critical infrastructures that are vital both for DoD to perform its missions and for the survival of the American people.

EXECUTIVE SUMMARY

As described in this report, there is a need to have bounding information for the late-time (E3) high-altitude electromagnetic pulse (HEMP) threat waveform and a ground pattern to study the impact of these types of electromagnetic fields on long lines associated with the critical infrastructures. It is important that this waveform be readily available and useful for those working in the commercial sectors.

While the military has developed worst-case HEMP waveforms (E1, E2, and E3) for its purposes, these are not available for commercial use. Therefore, in this report openly available E3 HEMP measurements are evaluated from two high-altitude nuclear tests performed by the Soviet Union in 1962. Using these data waveforms and an understanding of the scaling relationships for the E3 HEMP heave phenomenon, bounding waveforms for commercial applications were developed.

Since the measured quantities during these tests were the magnetic fields, it is possible to compute the electric fields assuming ground conductivity profiles that produce significant levels. There are other profiles that would compute even higher electric fields, but some of these profiles do not cover a very large area of the Earth.

After computing the electric fields using the Soviet measurements, the results were scaled to account for the fact that their measurement locations were not at the optimum points on the ground to capture the maximum peak fields. Through this process, it was determined that the scaled maximum peak E3 HEMP heave field would have been 66 volts per kilometer (V/km) for the magnetic latitude of the Soviet tests.

As the E3 HEMP heave field also increases for burst points closer to the geomagnetic equator, the measured results were also evaluated for this parameter. This scaling increases the maximum peak electric field up to 85 V/km for locations in the southern part of the continental U.S., and 102 V/km for locations nearer to the geomagnetic equator, as in Hawaii. The levels in Alaska would be lower at an estimated peak value of 38 V/km (see Table 5 for information dealing with this scaling process).

It is noted that this report does not claim that the values provided here are absolute worst-case field levels, but rather these peak levels are estimated based directly on measurements made during Soviet high-altitude nuclear testing.

1 INTRODUCTION

Over many years beginning in the 1980s, the U.S. has worked to establish the peak field levels, ground patterns of the heave portion of the late-time E3 HEMP fields as shown in Figure 1, and from these to build useful models.[1,2] In the summer of 1994, Soviet scientists attending the European Electromagnetics (EUROEM) Symposium in Bordeaux, France, presented several papers indicating their understanding of the different types of EMP including the high-altitude electromagnetic pulse (HEMP). One of the most interesting developments of that conference was that these presentations summarized the Soviet high-altitude electromagnetic test results and indicated that the most important aspects of the effects they observed were caused by the "long tail" of the HEMP.[3] In later publications, they indicated that the long tail referred to the late-time HEMP, or the E3 HEMP magnetohydrodynamic (MHD)-EMP heave signal, and later provided detailed technical information indicating that the failure of one long-haul communications line was due to this portion of the HEMP.[4] Three other references dealing with E3 HEMP (MHD-EMP) were published by Soviet scientists in this time frame presumably due to their interest in understanding the failures of commercial long line systems during their 1962 high-altitude nuclear testing program over Kazakhstan.[5,6,7]

Later in the early 2000s, Soviet scientists provided the EMP Commission with a memo that illustrated their magnetic field measurements of the E3 HEMP heave signals at three locations during two of their high-altitude nuclear tests over Kazakhstan in 1962.[8] Because the Soviets tested over land instead of over ocean, as did the U.S., several long line systems were affected by the E3 HEMP fields. In addition, measurements of the magnetic fields were made at several locations on the ground at various ranges from the surface zero (the point directly underneath the high-altitude burst).

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1 J. Gilbert, J. Kappenman, W. Radasky and E. Savage, "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid," Meta R-321, January 2010.

2 J.L. Gilbert, W.A. Radasky, K.S. Smith, K. Mallen, M.L. Sloan, J.R. Thompson, C.S. Kueny and E. Savage, "HEMPTAPS/HEMP-PC Audit Report." Meta R-131, December 1999; DTRA-TR-00-1, April 2002.

3 V.M. Loborev, "Up to Date State of the NEMP Problems and Topical Research Directions," Proceedings of the European Electromagnetics International Symposium -- EUROEM 94, June 1994, pp. 15-21.

4 V.N. Greetsai, A.H. Kozlovsky, V.M. Kuvshinnikov, V.M. Loborev, Y.V. Parfenov, O.A. Tarasov and L.N. Zdoukhov, "Response of Long Lines to Nuclear High-Altitude Nuclear Pulse (HEMP)," IEEE Transactions on EMC, Vol. 40, Issue 4, 1998, pp. 348-354.

5 V.N. Greetsai, V.M. Kondratiev, and E.L. Stupitsky, "Numerical Modelling of the Processes of High-Altitude Nuclear Explosion MDH-EMP Formation and Propagation," Roma International Symposium on EMC, September 1996, pp. 769-771.

6 "The Physics of Nuclear Explosions," Ministry of Defense of the Russian Federation, Central Institute of Physics and Technology, Volumes 1 and 2, ISBN 5-02-015124-6, 1997. MHD-EMP topics are found in Sections 13.5 and 13.6.3.

7 V.M. Kondratiev and V.V. Sokovikh, "Redetermination of MHD-EMP Amplitude Characteristics and Spatial Distribution on the Ground Surface," Roma International Symposium on EMC, September 1998, pp. 129-132.

8 "Characteristics of magnetic signals detected on the ground during the Soviet nuclear high-altitude explosions," memorandum provided by Soviet scientists, February 2003.

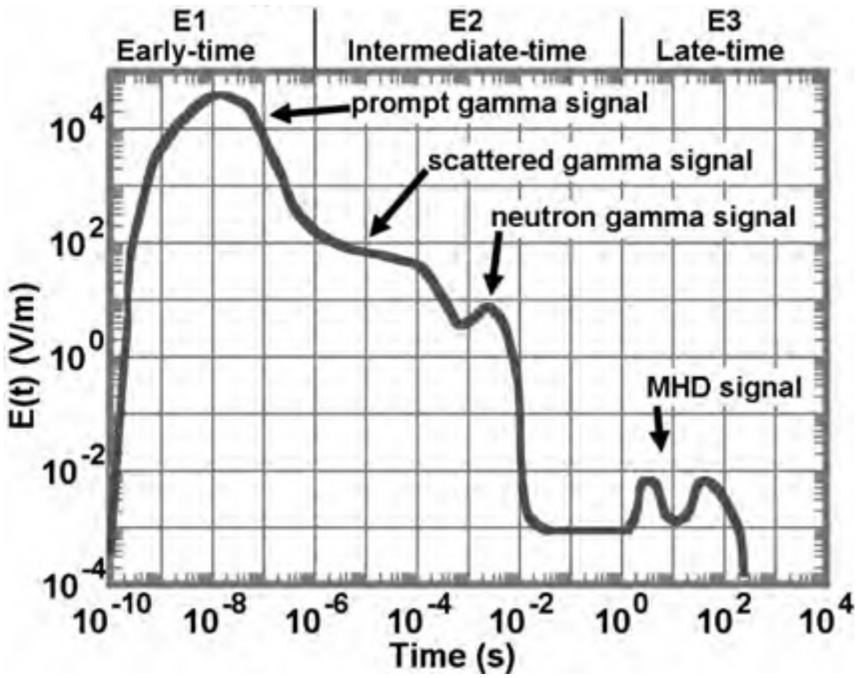

Figure 1 Parts of HEMP. E3 HEMP heave is roughly described by the second peak in the MHD signal. [SOURCE: Meta R-321]

In this report, the Soviet magnetic field data is reviewed, and through the use of several different ground conductivity profiles for locations in the U.S., the electric fields at the Earth's surface that could be induced are calculated. The magnetic fields are created by the nuclear detonation and the electric fields are induced in the earth and vary due to the particular deep conductivity profiles in the Earth. In addition, the magnetic fields (and electric fields) were also scaled to account for the fact that the Soviet measurements were not at the optimum ground locations to obtain the maximum peak fields on the ground. Finally, the increases in peak fields that would occur due to the well understood scaling of E3 HEMP with magnetic latitude were estimated, as the latitude of the Soviet tests were not at the bounding locations on the Earth.

The objective of this report is to determine from open source information how high the electric fields could be at latitudes of interest for the United States. In addition, a ground pattern and typical normalized electric field waveform is estimated that could be used for studies to determine the levels of quasi-DC currents that could be induced in long-line systems such as the bulk power system.

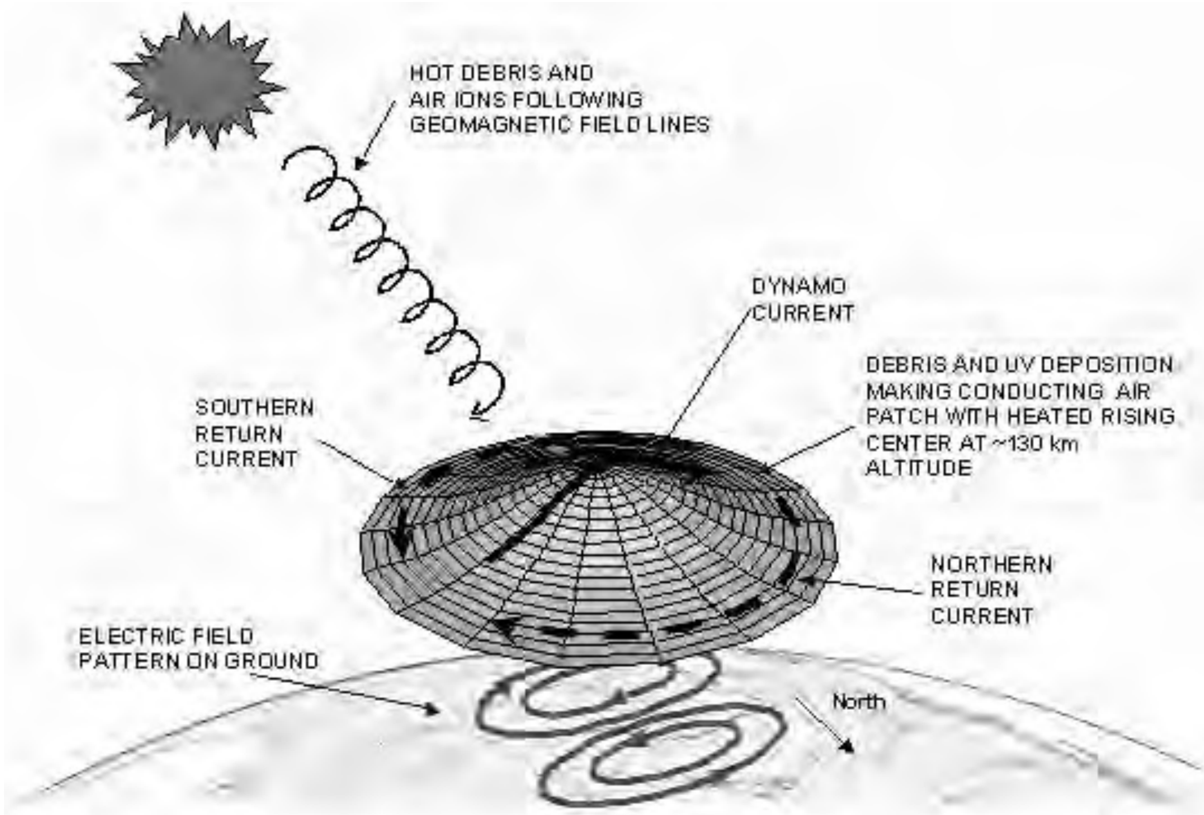

Figure 2 Diagram of the E3 HEMP heave effect. [SOURCE: Meta R-321]

This report does not claim that the values suggested here are absolute worst-case field levels, but rather these peak levels are estimated based directly on measurements made during high-altitude nuclear testing.

Figure 2 represents the E3 HEMP heave generation process. Hot ionized debris streaming downward away from the burst is directed preferentially along the geomagnetic field lines. As the debris and ultraviolet (UV) radiation from the burst reach altitudes where the atmosphere becomes dense enough, they heat up a “patch” of the atmosphere, and also add ionization to the background ionization already present in the ionosphere. The heat causes expansion, and the ionized region rises due to buoyancy. The Lorentz force on the ions and free electrons moving upward in the Earth’s geomagnetic field leads to east-west dynamo currents, with return currents completing the current flow on the north and south side. These currents induce image currents, with the associated electric fields, in the conductivity of the Earth below. Associated with this are magnetic (B) fields. The levels of the generated E fields are dependent on the actual ground conductivity to great depths of the Earth below the heaving patch, while the associated B field perturbations are approximately independent of the ground profile. For

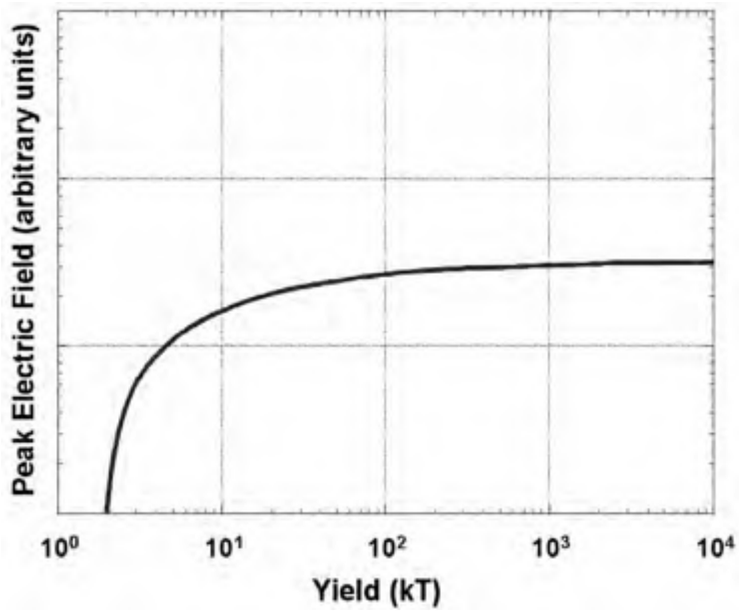

Figure 3 Sample normalized yield variation for maximum E field for heave for burst heights between 130 and 170 km and for a fixed Earth conductivity profile. [SOURCE: Meta R-321].

this reason, the measured B fields on the Earth's surface can be considered to be the principal E3 HEMP heave environment.

It is noted that there is a second mechanism that creates E3 HEMP fields on the ground called "Blast Wave", but while it also can produce significant B fields, the maximum fields are found thousands of kilometers away from ground zero. For this reason, the Blast Wave phenomenon is not considered in this report.

The E3 HEMP heave B field perturbation on the ground depends on many parameters, such as:

1. Burst parameters: The characteristics of the burst are important. Of primary importance is the burst yield—bigger bombs would tend to have more debris coming down and generating the E3 HEMP heave signal. Figure 3 shows a sample of E3 HEMP heave variation with yield. This yield dependence can vary with the burst height. In addition, the area of coverage for the peak field tends to be larger for larger yields.
2. Burst location: The burst location has two important effects. First, the height of burst (HOB) is important for E3 HEMP heave, as it is for other HEMP phenomena. The precise interaction with the atmosphere depends on how high the burst is above the atmosphere. Also, the higher the burst, the farther north (for northern hemisphere bursts) the heated patch is found, as it needs to travel a further distance on the tilted

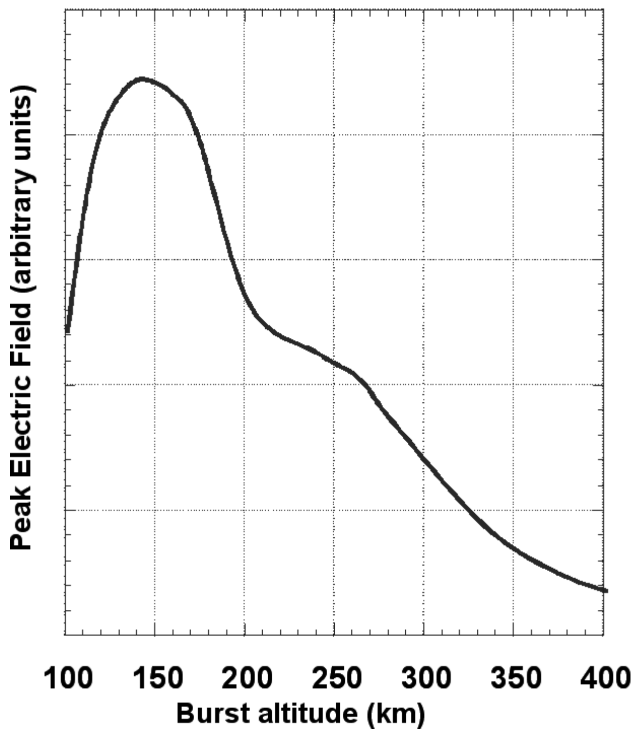

Figure 4 Sample normalized HOB variation for maximum peak E field for heave for an intermediate yield weapon and for a fixed Earth conductivity profile. [SOURCE: Meta R-321].

geomagnetic field lines. Figure 4 shows a sample of HOB variation for a fixed yield and ground conductivity profile. The other important location effect is the local geomagnetic field, which is represented by the value of geomagnetic latitude. One effect is that E3 HEMP heave gets weaker as the burst gets closer toward the (geomagnetic) poles, because the geomagnetic field becomes less horizontal, and there is less east-west deflection of the rising hot ions. (The geomagnetic latitude also affects the tilt of the path that the debris follows downward from the burst.)

3. Observer location: As seen in Figure 2, there is a 2-loop pattern of ground fields. The magnitude of the ground fields decreases with distance from the point directly below the patch. Examples of ground patterns are provided later in this report.
4. Burst time of day: Here the important factor is the "atmosphere", basically the state of the ionosphere, which can vary significantly. Depending on the burst time, the day of the year, and the location, the burst may be in "night" or "day". Sun exposure enhances the ionization of the ionosphere. For the E3 HEMP Blast Wave (the early-time portion of the E3 HEMP, which is not the subject of this report) the enhancement due to the "daytime" conditions depresses the E3 HEMP Blast Wave field, while for E3 HEMP heave there is an enhancement of the fields.

2 GROUND CONDUCTIVITY PROFILES

The E3 HEMP signal of concern in this report is the induced horizontal electric (E) field, as this field can effectively couple to long power and communications lines and induce quasi-dc currents in these systems. This coupling process has been discussed in several references including one that deals with geomagnetic disturbances (GMDs); GMD electric fields are similar in their time and frequency content to the electric fields produced by the E3 HEMP heave.[9] These E fields are produced by the presence of the conductivity depth profile in the Earth itself. For E3 HEMP heave it is the conductivity down to great depths (400-700 km) below the Earth's surface that determines the electric field. The E3 HEMP generation process begins with magnetic field (B) perturbations (relative to the geomagnetic field created by the Earth's core), and at the Earth's surface these B fields are little affected by the ground conductivity profile. Thus both calculations and measurements for actual nuclear tests typically begin with the B fields, and then E fields can be calculated for any assumed ground conductivity profile. While the induced peak E field is strongly related to the time derivative (dB/dt) of the horizontal B field, these calculations use the full Maxwell's Equations to determine the electric fields. The resulting E field is also horizontally oriented. The calculation of E from B must be done in terms of vector components—a B field in one horizontal direction creates an E field that is perpendicular to it under an assumed one-dimensional approximation for the local Earth conductivity profile.

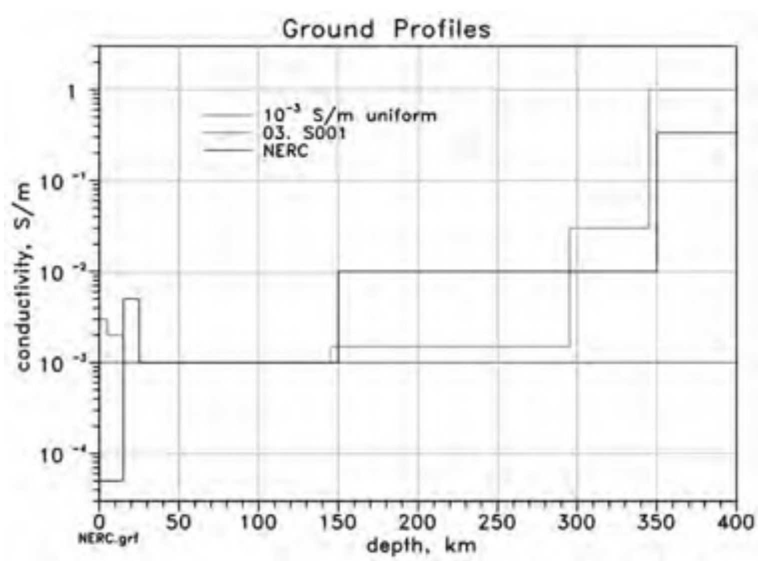

Figure 5 Ground conductivity depth profile for three ground profiles.

Figure 5 shows three ground profiles of ground conductivity with depth used in this report. The NERC profile (red line) has four layers of various conductivity levels, ending at a high

[9] W.A. Radasky, "Overview of the Impact of Intense Geomagnetic Storms on the U.S. High Voltage Power Grid," IEEE Electromagnetic Compatibility Symposium, Long Beach, California, 15-19 August 2011, pp. 300-305.

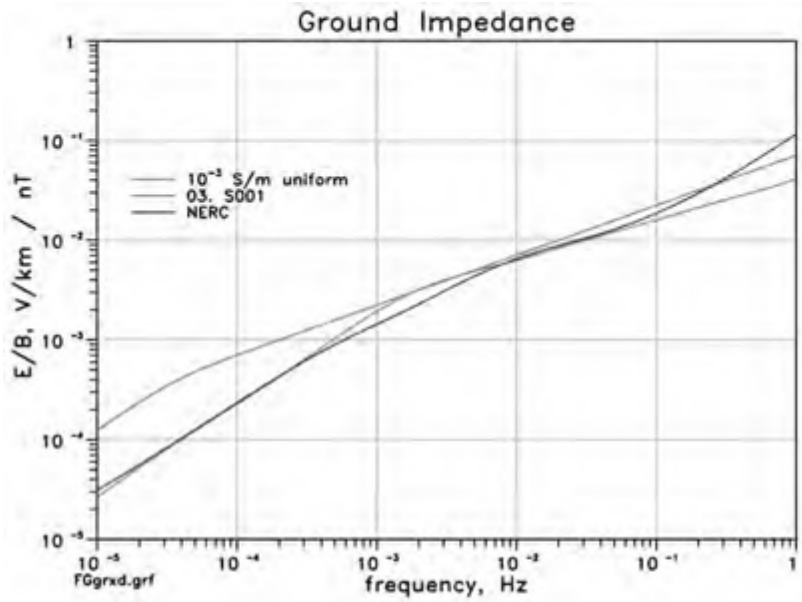

Figure 6 Ground profile B-to-E conversion in the frequency domain for three cases.

conductivity level that continues downward at its last value.[10] The E3 HEMP heave signals (due to their low frequency content) can penetrate through the upper layers of the Earth but will not penetrate much deeper when they encounter a high conductivity lower level (due to the pressures and temperatures found in the upper mantle of the Earth). The blue line is another set of ground conductivity data applicable to eastern Canada developed by Metatech from geological data. The impedance curve developed from this conductivity profile is seen to be very similar to the NERC curve in Figure 6. The third profile shown (in green) has a uniform conductivity of 10^{-3} S/m, which is used for simplicity in the E3 HEMP heave simulations shown later in this report.

Figure 6 shows the resulting impedance (conversion of B to E) in the frequency domain. There are many ways to deal with these types of impedance curves relating E to B, although the technique used by the authors allows calculations of E from B in the time domain without converting to the frequency domain.[11] This has advantages for performing real-time computations when measuring geomagnetic storm disturbances. All three curves are reasonably close together for the important frequency range of 1 to 100 mHz, as this is the frequency range of typical E3 HEMP B-field disturbances.

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10 "Transmission System Planned Performance for Geomagnetic Disturbance Events", TPL-007-1, available at https://bit.ly/2GQpQF1

11 J.L. Gilbert, W.A. Radasky and E.B. Savage, "A Technique for Calculating the Currents Induced by Geomagnetic Storms on Large High Voltage Power Grids," IEEE EMC Symposium, Pittsburgh, August 2012, pp. 323-328.

3 SOVIET E3 HEMP MEASUREMENTS

Toward the end of the development of the E3 HEMP computational models in the U.S., a paper that reported measurements made by the Soviet Union during two of their high-altitude nuclear tests in 1962 was provided to us through the U.S. Congressional EMP Commission by Soviet scientists.[12] This was high quality data, in that measurements were made at three fixed locations (designated N1, N2, and N3 by the Soviets as shown in Table 1 and Figure 7), and the B field measurements were provided for two horizontal vector components. There is some uncertainty concerning the precision of the test and measurement locations; however, the data provided greatly increased the information describing the E3 HEMP heave signal. High-altitude nuclear tests were performed by the U.S. mainly over the Pacific Ocean, and the locations for measuring the magnetic fields were not as diverse as for the Soviet measurements.

TEST PARAMETERS

The Soviet tests were reported to be at burst heights of 150 and 300 km altitudes, for the same device design with an estimated yield of 300 kT. The precise geometry (burst and observer locations) is not known, as there was some ambiguity in the data provided. The Soviet measurement paper does give range values (burst to observer distances) for all six measurements (three from each test), and these same values appear elsewhere in a consistent manner. (The Soviets tended to use the slant range from the burst to the ground location, not the ground range, but the ground range is easily calculated from the burst height.) A set of locations was used that are consistent with these values in the following discussions, using the understanding of the variation of the fields with location. These burst and observer locations are given in Table 1.

Table 1 Geometry for the Soviet High-Altitude Tests.

Test Locations

Type	Position	Latitude (N)	Longitude (E)
Bursts	R1, 300 km	47.6°	64.9°
	R2, 150 km	47.0°	68.0°
Observers	N1	47.9°	67.4°
	N2	47.1°	70.6°
	N3	45.9°	72.1°

12 "Characteristics of magnetic signals detected on the ground during the Soviet nuclear high-altitude explosions," memorandum provided by Soviet scientists, February 2003.

Using the simulation code in Meta R-321, the B field peak values were calculated for the two burst heights. The data is shown in Figure 7 for the 150 km burst height (R1) and in Figure 8 for 300 km (R2).[13] (The 300 km test was actually performed 6 days before the 150 km test, but the lower altitude case was described first). The peak contours are identified by their color, and the B field directions at the time of the peak are shown by the arrows. The burst and observer points are marked on the displays. Normalized results are shown in these figures as a nominal contour plot is desired to be used later in this report as a standard contour profile.

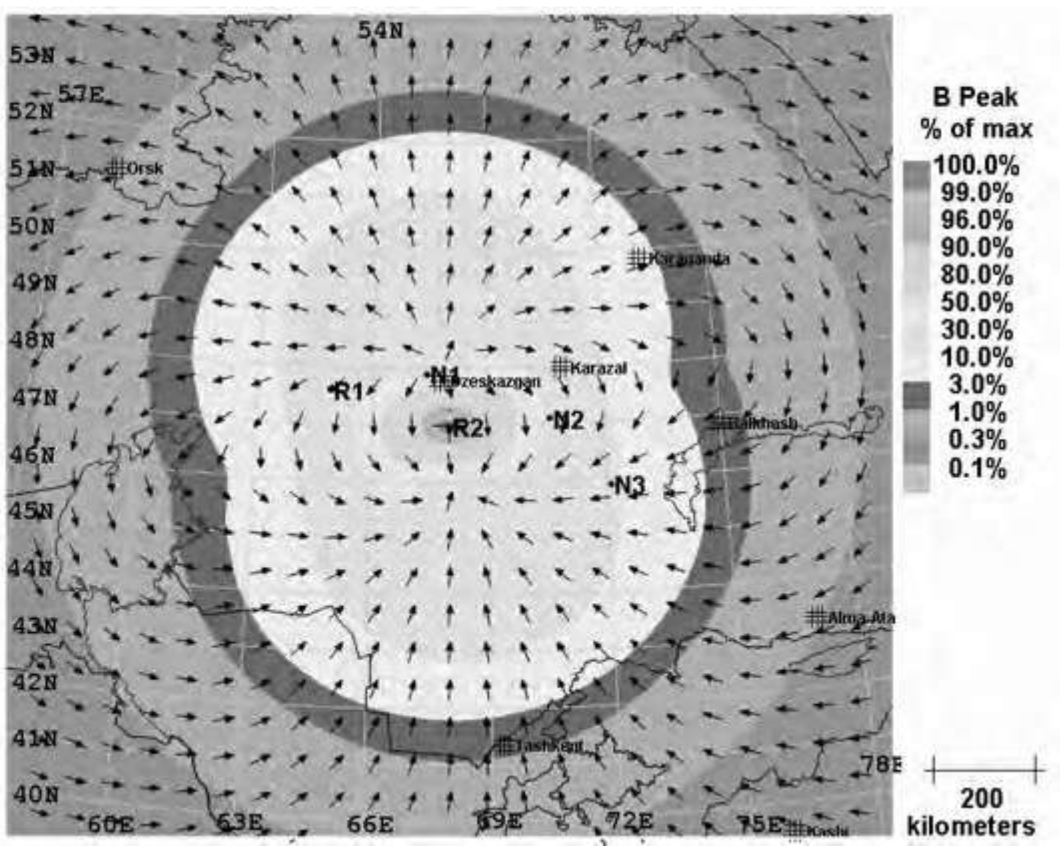

Figure 7 Simulation of the Soviet tests showing B field peaks and field directions,150 km test (R2).

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13 J.L. Gilbert, W.A. Radasky, K.S. Smith, K. Mallen, M.L. Sloan, J.R. Thompson, C.S. Kueny and E. Savage, "HEMPTAPS/HEMP-PC Audit Report." Meta R-131, December 1999; DTRA-TR-00-1, April 2002.

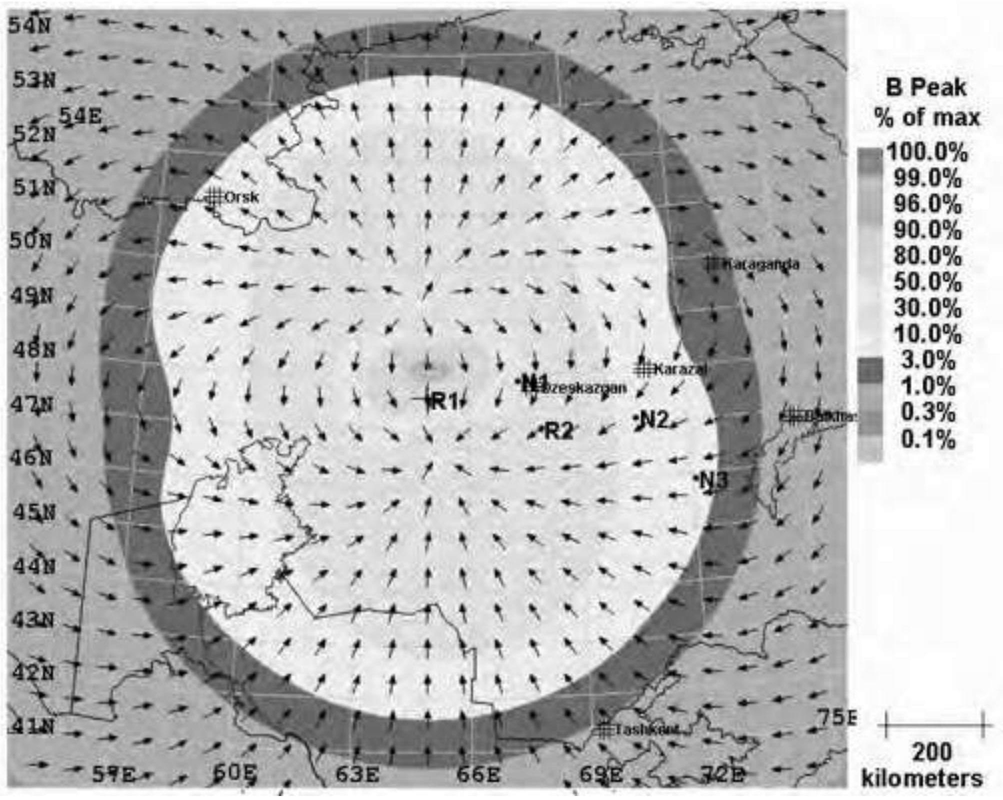


Figure 8 Simulation of the Soviet tests showing B field peaks and field directions, 300 km test (R1).

The next set of figures shows the measured B field time waveforms. The three lines are the north and west components, and the resulting magnitude. For the 150 km burst height case, shown in Figure 9 to Figure 11, the waveforms are all relatively wide in pulse width (the N1 case waveform has not returned to zero at the end of the 100-second window of the measurements). The peak occurs between times of 35 to 70 seconds. Figure 7 shows that N1 is close to the northern area of the two electric field depression points (the locations around which the two loops of E field circulate, as seen earlier in Figure 2) for this case. Here the time waveform may be complicated due to some shifting with time of the field depression point position. For the 300 km burst height waveforms, Figure 12 to Figure 14, the signals are faster, especially for N1. As noted, faster rising waveforms for the B fields enhance the E fields, because the impedance of the Earth behaves as $f^{1/2}$ (f = frequency) as shown in Figure 6.

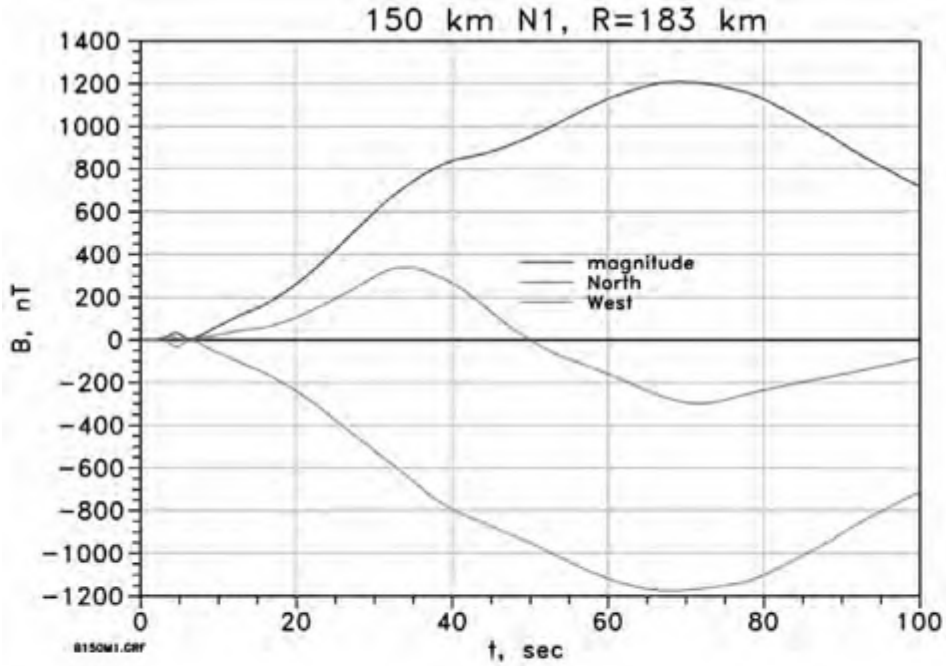


Figure 9 Measured B fields at N1, 150 km test.

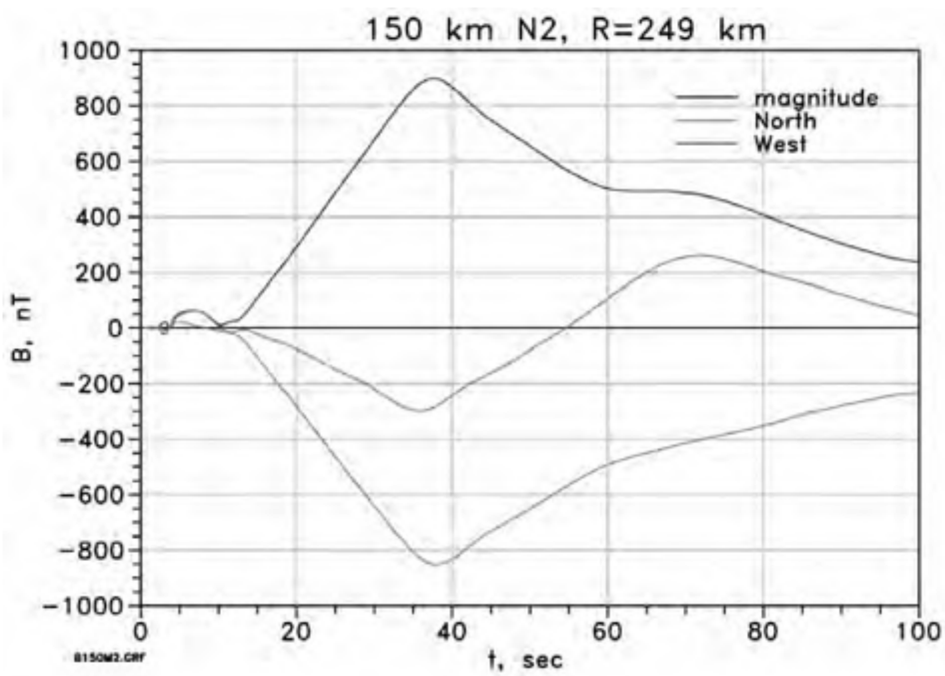


Figure 10 Measured B fields at N2, 150 km test.

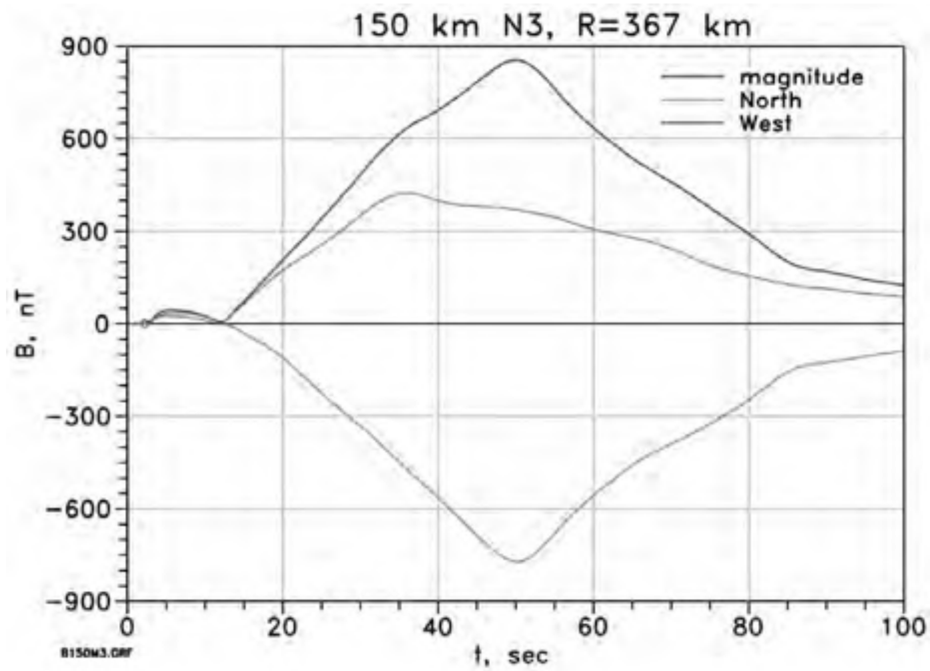


Figure 11 Measured B fields at N3, 150 km test.

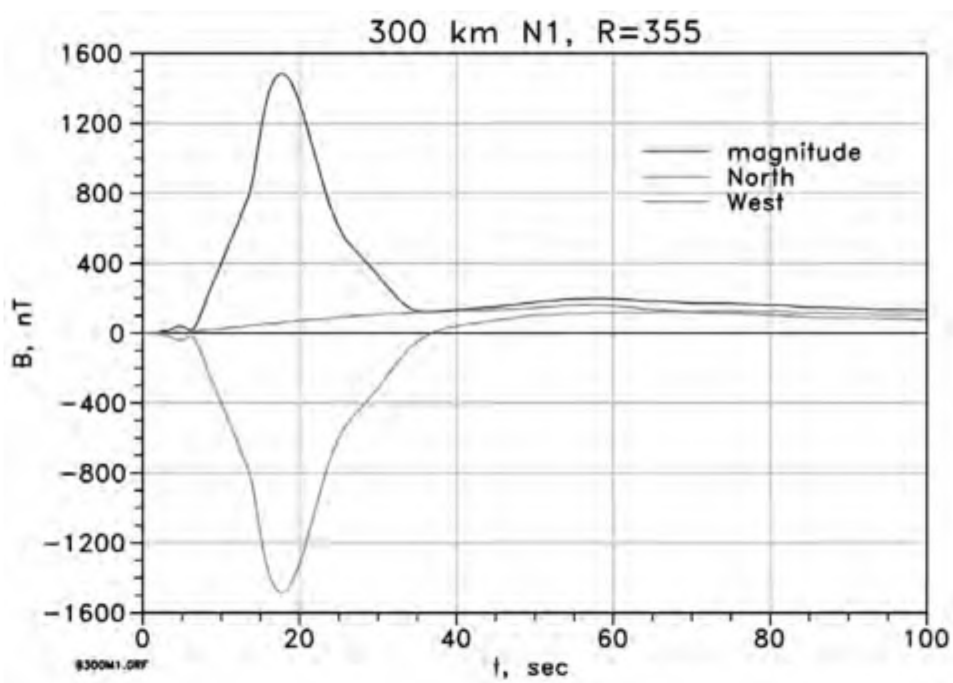


Figure 12 Measured B fields at N1, 300 km test.

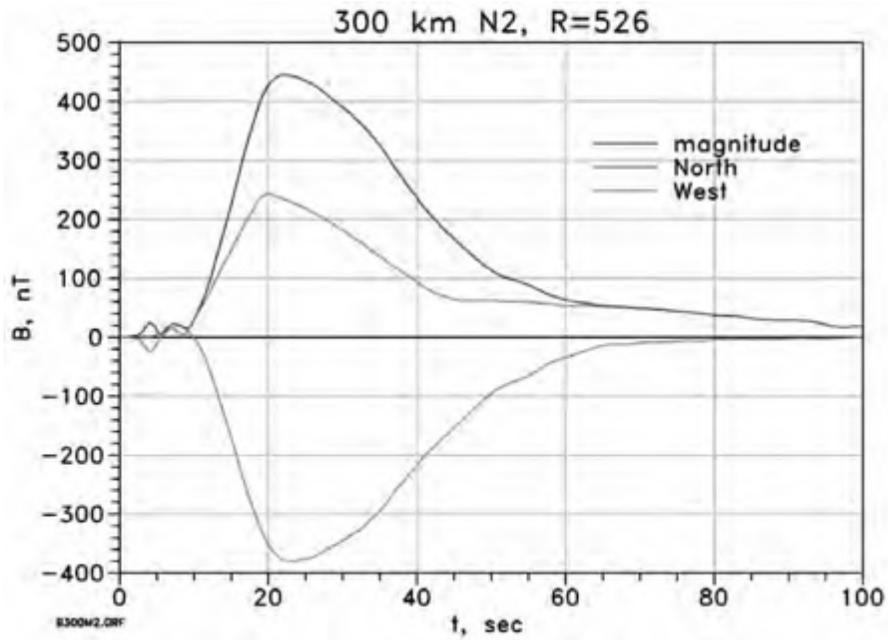


Figure 13 Measured B fields at N2, 300 km test.

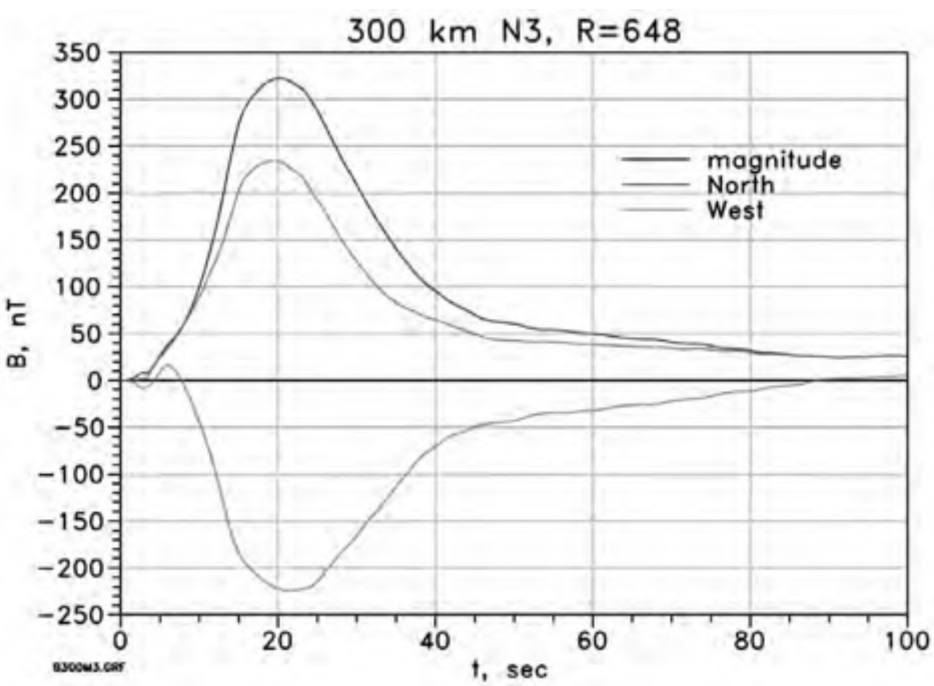


Figure 14 Measured B fields at N3, 300 km test.

The electric fields are now calculated from the measured B fields, given in nanoTeslas (nT). Table 2 lists the peak values for the calculated E fields, along with the peak values for the measured B and B-dot. The time derivative of B is often a good proxy for the behavior of the peak value of the electric field for a given ground conductivity profile. That is to say that for a given profile increases in the time derivative of the B field result in higher peak electric fields. It is noted, however, that the rest of the computed time waveform of the electric field depends more on the shape of the impedance curve and using the time derivative of the B field to compute the entire electric field waveform will not result in an accurate E field waveform.

For the following plots the measured B field components were individually computed for four sample ground profiles (a fourth severe ground profile and impedance curve was added to the previous set of three), and the resulting E field magnitudes are plotted (the total horizontal electric field is calculated by separately calculating the electric fields from the two orthogonal B field components). The 150 km cases are presented in Figure 15 to Figure 17, and the 300 km cases are presented in Figure 18 to Figure 20. These show that E fields are similar for the three ground profiles described in Figure 6. Further, the dark blue line shows the E field for a ground profile that has a very low conductivity. This profile was developed for southern Sweden and has also been used for a limited region in the northeastern United States, but it has not been used to develop the E3 HEMP results here. It is presented only to indicate that large electric fields are possible in some locations.

The highest computed E fields are for the N1 observer for the 300 km burst case. This had the highest measured B fields, and also had the narrowest time waveform—the computed peak E fields are driven higher by the enhanced time derivative of the B.

Table 2 Peaks of the Soviet measurement waveforms. (The E field is for the 10^{-3} S/m ground.)

Measurement Peaks

Burst	Observer	Peaks		
		B, nT	$\dot{B}$, nT/min	E, V/km
R2 150 km	N1	1208.99	2141.2	4.885
	N2	898.27	3526.3	5.580
	N3	856.08	2240.2	4.241
R1 300 km	N1	1484.05	17581.4	16.585
	N2	444.69	3064.8	4.110
	N3	322.57	2642.9	3.113

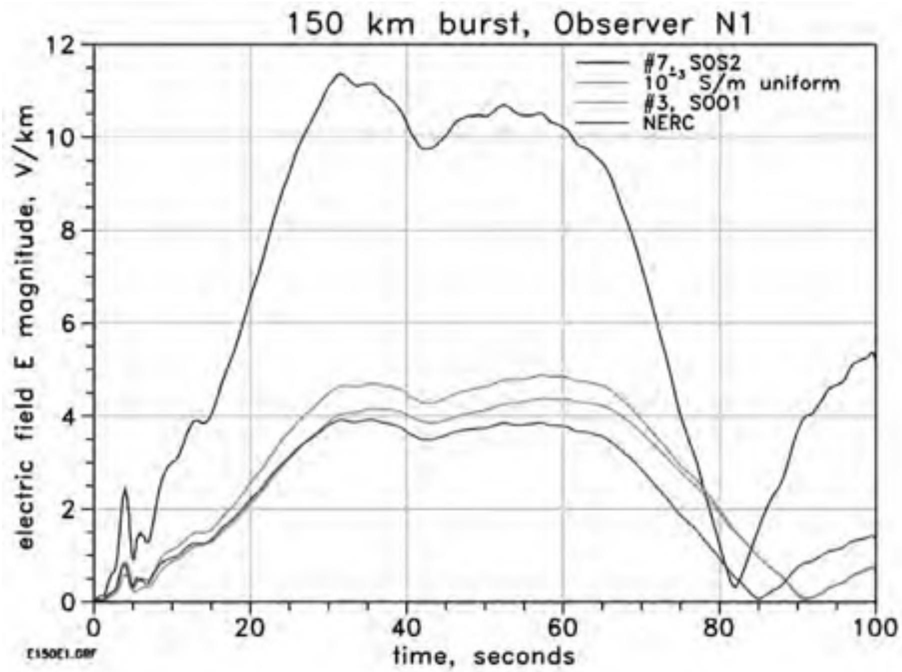


Figure 15 E field amplitudes for four ground profiles, at N1, 150 km test.

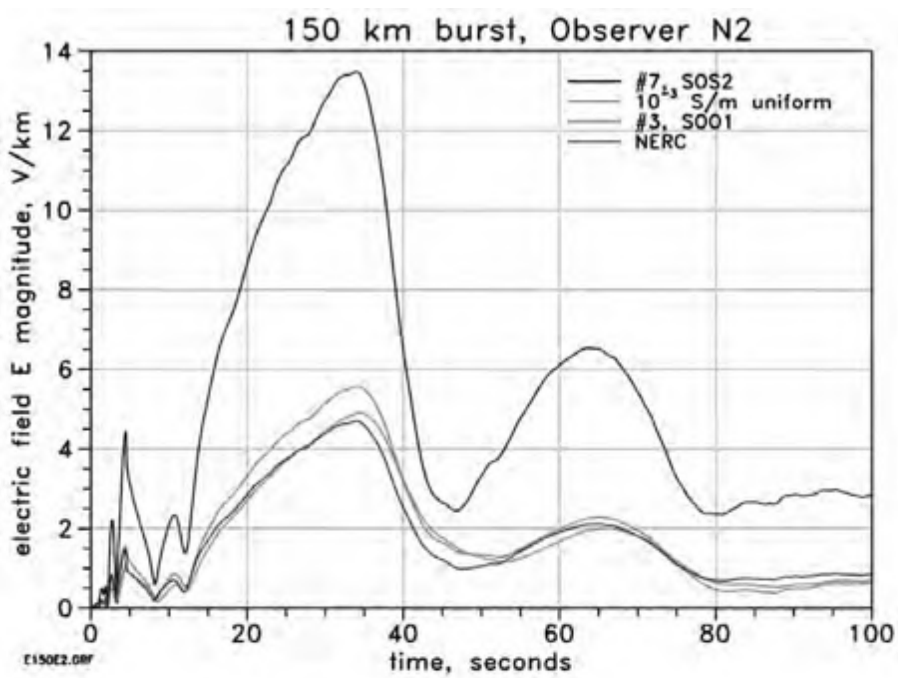


Figure 16 E field amplitudes for four ground profiles, at N2, 150 km test.

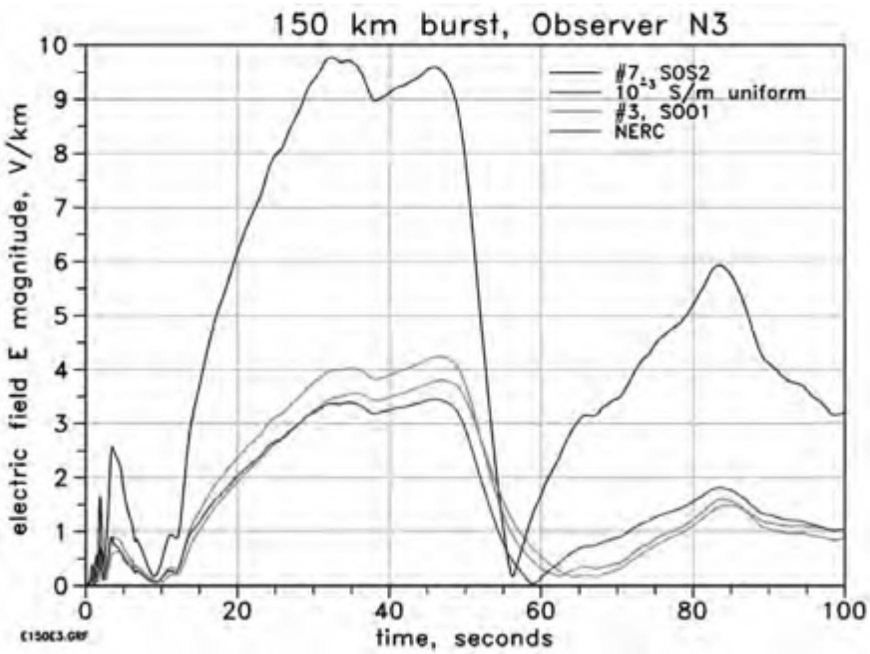


Figure 17 E field amplitudes for four ground profiles, at N3, 150 km test.

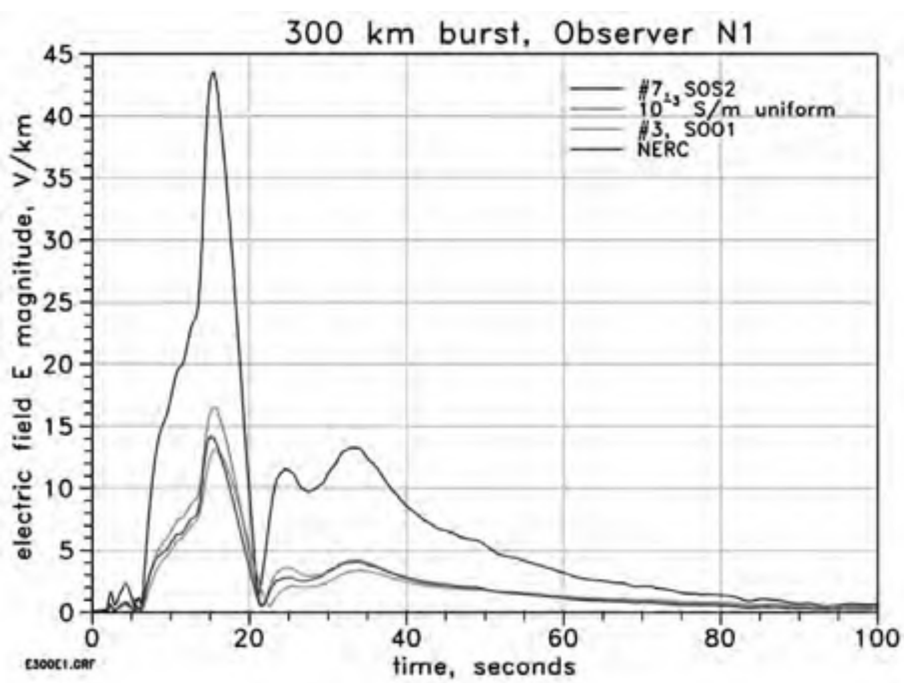


Figure 18 E field amplitudes for four ground profiles, at N1, 300 km test.

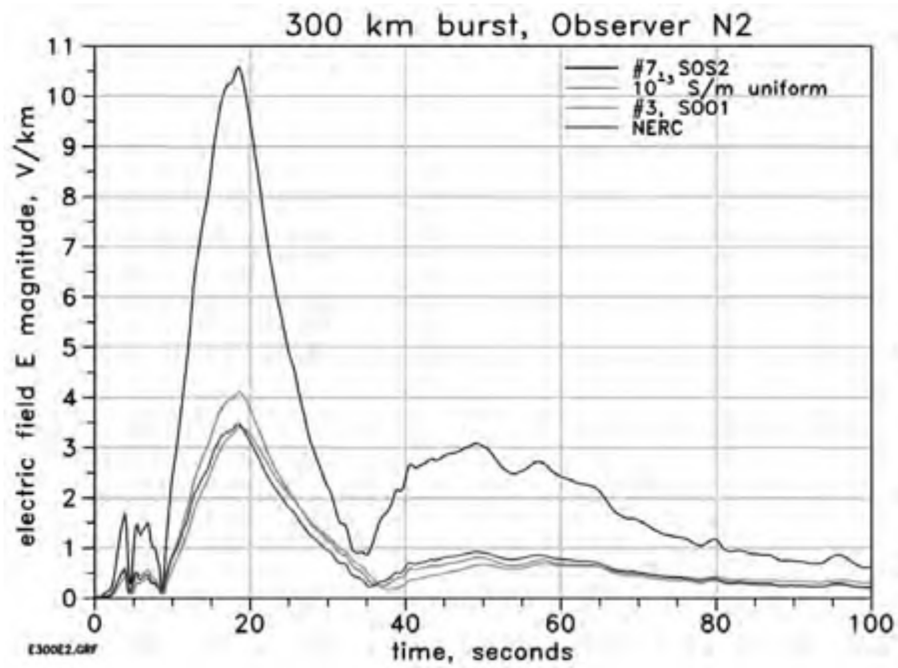


Figure 19 E field amplitudes for four ground profiles, at N2, 300 km test.

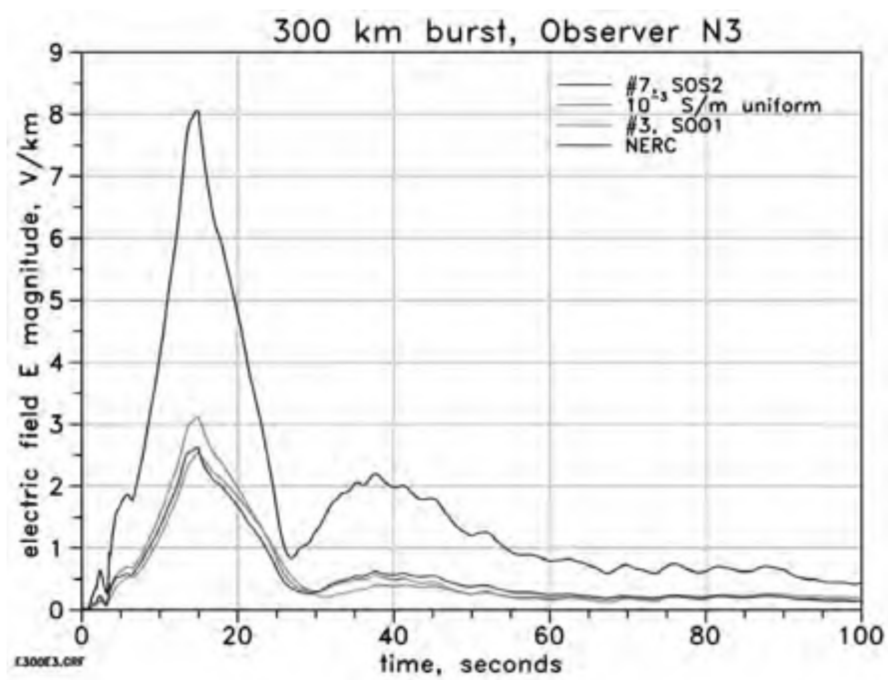


Figure 20 E field amplitudes for four ground profiles, at N3, 300 km test.

SCALING OF THE RESULTS

Even at this date the calculational models of E3 HEMP heave are not considered to be perfect, and therefore measurements are the most believable evidence of possible E3 HEMP heave field levels. However, it is extremely unlikely that even these few high-quality measurements captured the highest peak fields. Of course other test devices, especially with higher yields, could have produced higher fields, and there can be vast variations in the atmosphere conditions. For this report, the parameters of interest are the locations of the measurement observers and of the burst itself. Specific parameters are the impacts due to the geomagnetic latitude of the bursts, and whether a better location exists to place measurement sites relative to each burst. The first question is: how much higher could the measured fields have been if the burst location were closer to the geomagnetic equator? The second question is because the fields were measured at only three locations, none of which were likely to have been at the optimum point, can the measurements be scaled to the optimum point?

LATITUDE SCALING

The first consideration is the geomagnetic latitude. The geomagnetic latitude values for the two cases are found from the given physical locations:

150 km: 48.92° N
300 km: 46.13° N

These values depend on knowing the burst locations, for which there is some uncertainty, but the precise values were likely within a few degrees of these values. As discussed, the maximum peak magnetic fields increase for lower geomagnetic latitudes per the basic models.

Considering the 150 km burst case, Figure 21 shows the equivalent locations for the continental U.S. The marked red lines show geomagnetic latitude lines, and there is a black line for the 48.92°N magnetic latitude corresponding to the 150 km HOB Soviet test. If the burst had been placed anywhere along this line, the maximum peak B fields would have been as in the Soviet test. For bursts below (south) this black line, the fields would be higher.

The map shows that Texas and Florida can be as low as 35°N geomagnetic latitude. The simulation code used to perform the calculations was the same as used for the simulations shown in Figure 7 and Figure 8, but with the burst moved to lower geomagnetic latitudes—specifically the cases of 35°N that correspond to the southern points for Florida and Texas, and also for the highest levels worldwide (the geomagnetic equator). Next, the ratios of the maximum B fields from these simulations at other latitudes were compared to the maximum values for the Soviet measurement location, to get the results shown in Table 3. Using these ratio values, the Soviet measurements ("Soviet" column) were scaled to the corresponding maxima for the other latitude burst locations.

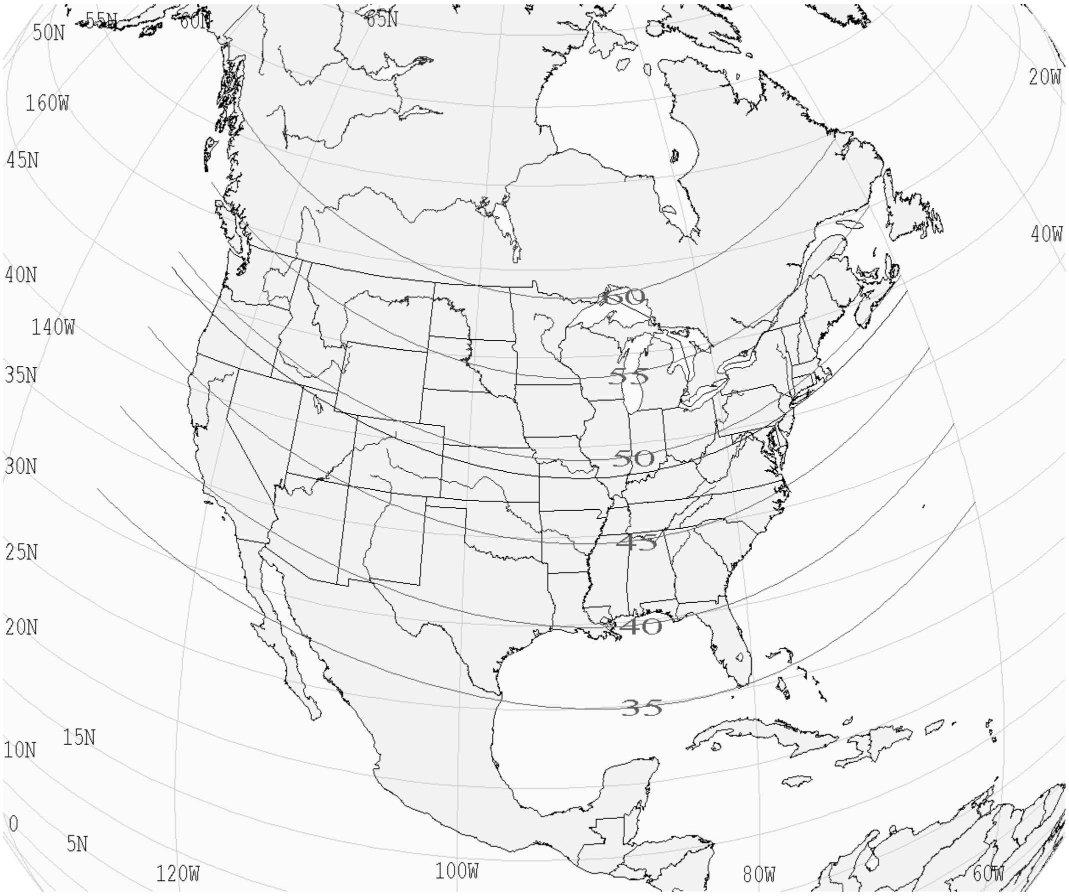


Figure 21 Geomagnetic latitude variation, for a 150 km burst, over the U.S. The black line is at 48.92°, which is the computed geomagnetic latitude for the 150 km Soviet test.

Locations outside of the continental U.S. include both lower and higher geomagnetic latitudes. The table therefore includes scaling for a magnetic latitude of 22° N, which is appropriate for Oahu, Hawaii, and also for a magnetic latitude of 65° N, as would apply to Fort Greely, Alaska.

PATTERN SCALING

The burst locations were different for the two tests, but the three observer locations stayed the same for the two tests. There is some uncertainty, however, in both the burst points and observer points. However, it is likely that the fields were higher at locations other than the three places that happened to be selected for the measurement sites. Here some understanding is sought for how high the measured fields might have been if there was a measurement at the optimal location. Figure 7 (the 150 km case), for example, shows that for this HOB the maximum is close to being directly under the burst, but the measurement sites were further out.

Table 3 Geomagnetic latitude scaling of the Soviet measurements.

Scaling of Measurements to Other Magnetic Latitudes

Burst (km)	Observer	Burst Locations						
		Soviet, B, nT	Alaska, 65° N		U.S., 35° N		Hawaii, 22° N	
			Scaling factor	B, nT	Scaling factor	B, nT	Scaling factor	B, nT
R2 150	N1	1208.99	0.600	725.28	1.364	1648.65	1.675	2025.50
	N2	898.27		538.88		1224.93		1504.93
	N3	856.08		513.56		1167.40		1434.24
R1 300	N1	1484.05	0.577	855.62	1.274	1890.47	1.537	2280.36
	N2	444.69		256.38		566.47		683.29
	N3	322.57		185.98		410.91		495.66

As noted, there is some uncertainty in the modeling and for the model parameters to use to simulate the Soviet tests. Good confidence exists, however, in the values for the ranges to the measurement sites. With this in mind, the simulation shown in Figure 22 performs E3 HEMP heave calculations at points on a 2D polar mesh; for each range of this mesh all the azimuth angles were searched to obtain three norm values: maximum, average, and minimum. The overall maximum was identified and the three norm values were normalized to this maximum value, to obtain the three lines in the plot.

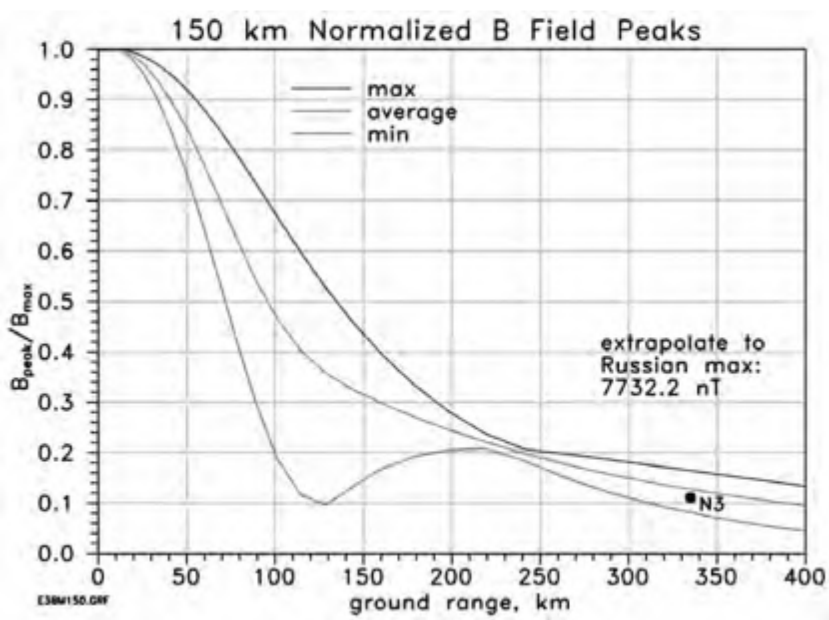


Figure 22 Normalized simulated B field peaks versus ground range for the 150 km test. The black dot

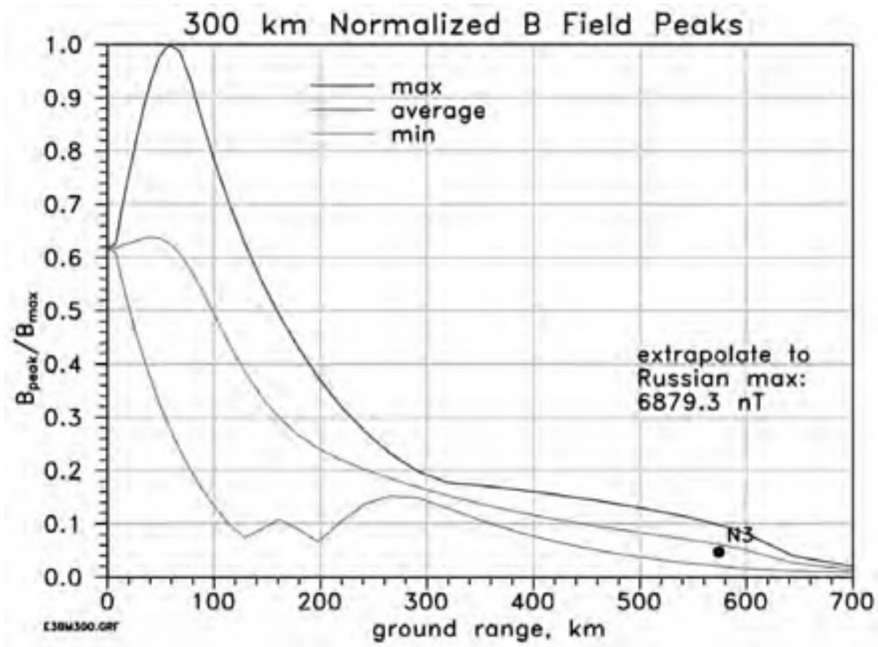


Figure 23 Normalized simulated B field peaks versus ground range for the 300 km test. The black dot shows the simulated results for the N3 point.

As noted, the precise observer azimuth positions are unknown, but the normalized value for the assumed position of the N3 observer is shown (the black dot) using a best-estimate location. Note that at this range there is not as much structure to the azimuth variation as there is closer in, such as at the 120 km range, so there is less uncertainty associated with the exact azimuth position for N3. Another way of stating this is to observe that the contour pattern becomes more circular as the observer is further away from surface zero. Using this pattern, the estimate for the maximum is then given by scaling with the factor of 9.03 (1/0.111) from the N3 point to the optimum position. The same method was used for the 300 km burst height, in the plot shown in Figure 23.

Table 4 summarizes the scaling for the two cases. The scaled values are listed in the last column. These are found by multiplying the N3 measurements (the 3rd column) by the scaling

Table 4 Pattern (observer position) scaling of the Soviet measurements.

Scaling from N3 up to the Maximum Point

	Soviet Measurements		Scaling	
Case	N1, B (nT)	N3, B (nT)	Scaling Factor	Max, B (nT)
R2, 150 km	1209.0	856.08	9.03	7732.2
R1, 300 km	1484.0	322.57	21.33	6879.3

factors (4th column, given by the reciprocal of the N3 values in Figure 22 and Figure 23). For comparison, the maximum measured values are listed in the 2nd column (the N1 points). The fact that these are smaller than the scaled maximum values is an indication that none of the observer points were very close to the optimum position.

4 CONCLUSIONS

The Soviet measurements of the E3 HEMP heave B fields were converted to E fields for a reasonable bounding case of a uniform ground conductivity of 1 mS/m. None of the three measurement points of the E3 HEMP heave fields were near the maximum in the expected field pattern, and column 3 in Table 5 gives estimates of the scaling of the measurements to the expected maximum. The three right columns provide the scaling for magnetic latitude to Hawaii, the southern portion of the continental United States, and Alaska.

Table 5 Scaling of the Soviet Measurements.

Scaling from N3 up to the Maximum Point, for Three Latitudes for 10^{-3} S/m

	Soviet Measurements		Latitude Scaling, E, V/km		
Case	Latitude (N)	E, V/km	22° N	35° N	65° N
R2, 150 km	48.92°	38.31	64.18	52.24	22.98
R1, 300 km	49.10°	66.39	102.02	84.57	38.28

Figure 24 provides a normalized waveform for one of the E fields. The electric field waveform can be used when computing the induced currents flowing in power lines, for example, to determine the amount of heating in transformer hot spots, as the time dependence of the currents are important in determining thermal effects. Figure 25 provides a sample normalized ground pattern, showing the spatial fall-off from the maximum value. Note that

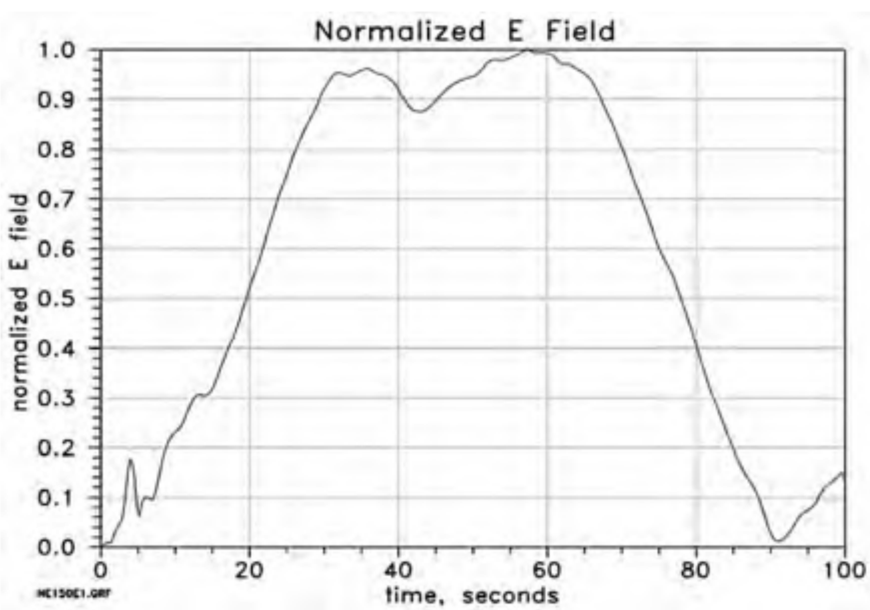


Figure 24 E field waveform shape, using the measured N1 waveform from the 150 km burst height

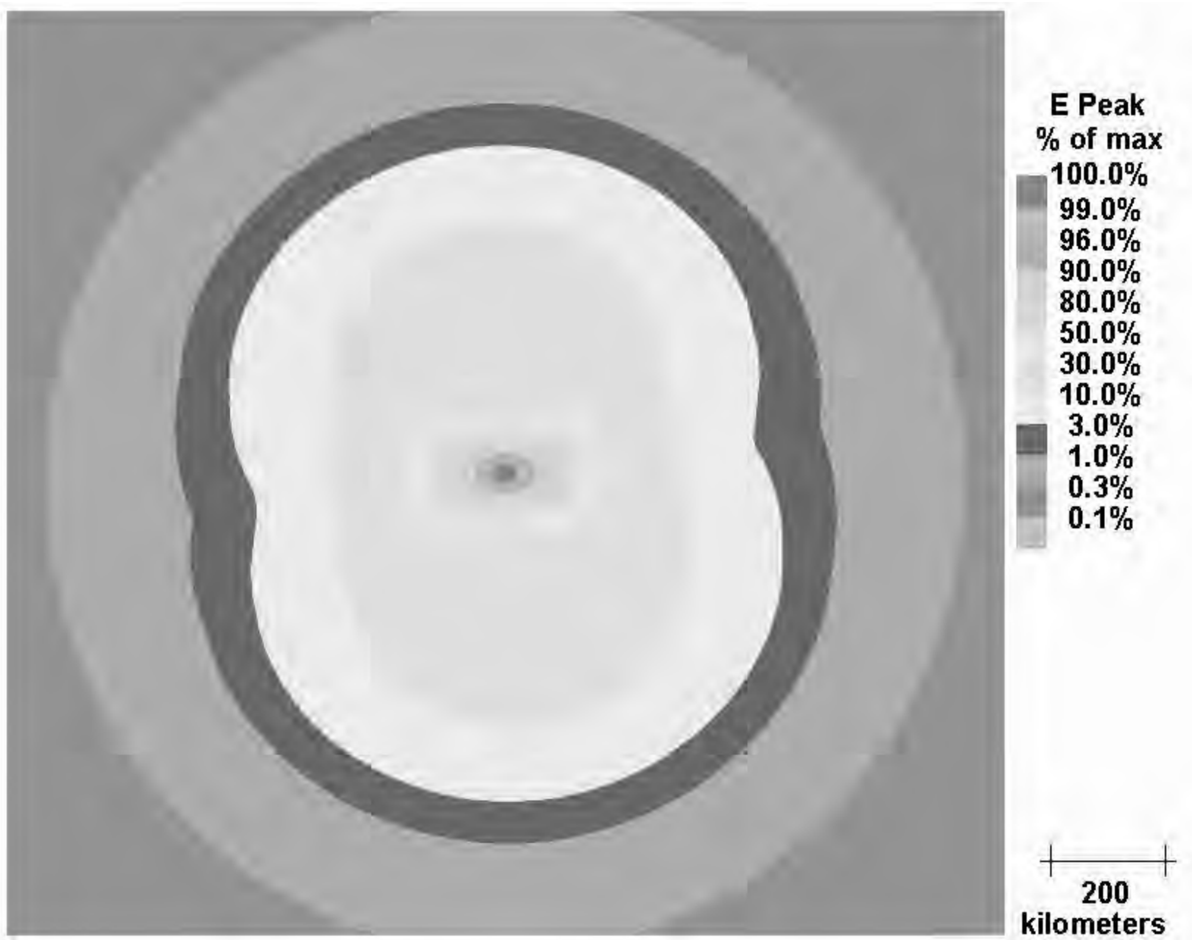
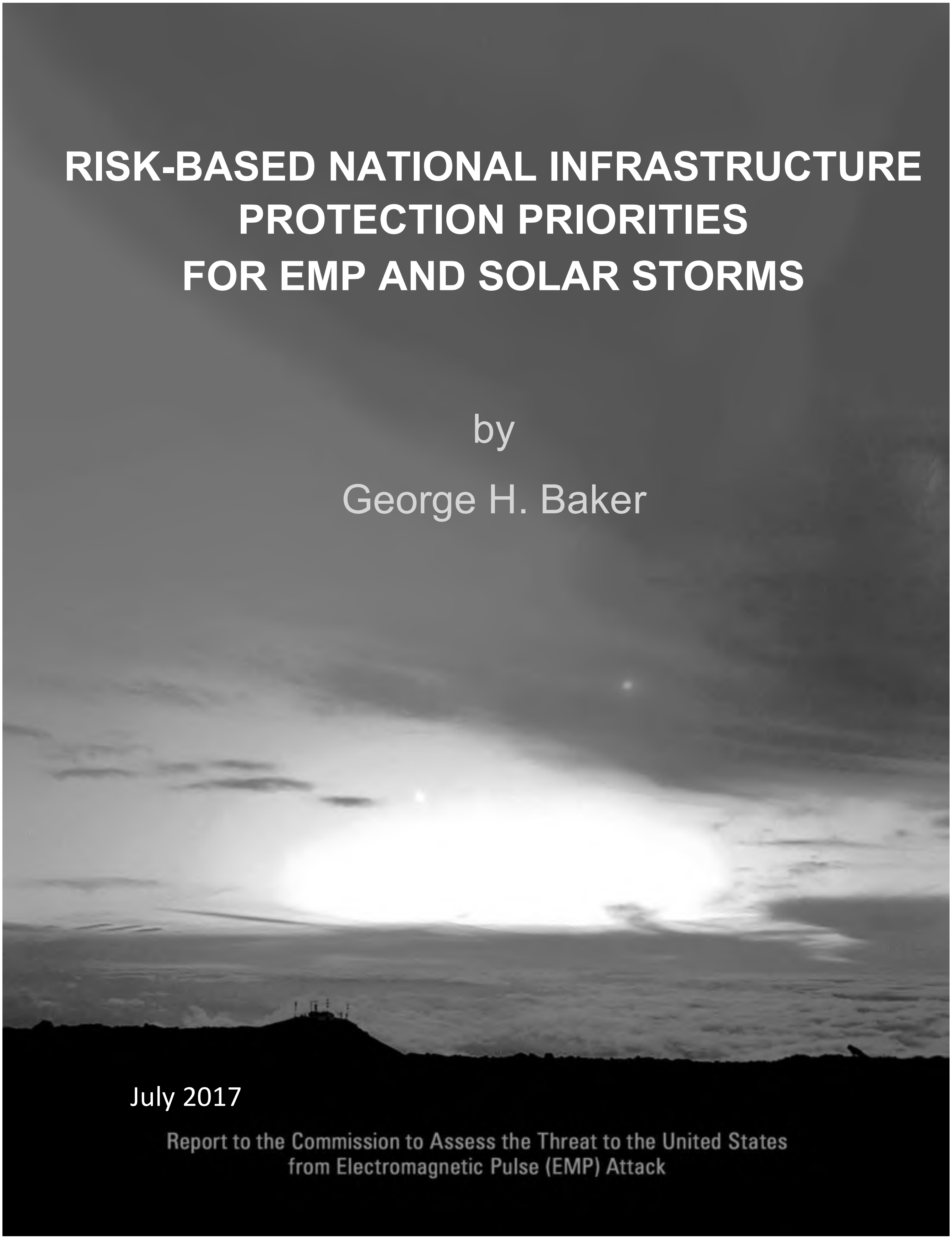


Figure 25 Normalized E peak contour pattern from the 150 km burst case

higher yield bursts could lead to even higher maximum fields, although as shown in the generic curve in Figure 3, the peak value tends to saturate as yields increase. However, this is not true for area coverage, as increasing to larger yields can increase the spatial extent of the high field region.



RISK-BASED NATIONAL INFRASTRUCTURE PROTECTION PRIORITIES FOR EMP AND SOLAR STORMS

by

George H. Baker

July 2017

Report to the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack

The cover photo depicts Fishbowl Starfish Prime at 0 to 15 seconds from Maui Station in July 1962, courtesy of Los Alamos National Laboratory.

This report is a product of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. The Commission was established by Congress in the FY2001 National Defense Authorization Act, Title XIV, and was continued per the FY2016 National Defense Authorization Act, Section 1089.

The Commission completed its information-gathering in June 2017. The report was cleared for open publication by the DoD Office of Prepublication and Security Review on June 5, 2018.

REPORT TO THE COMMISSION TO ASSESS THE THREAT TO THE UNITED STATES
FROM ELECTROMAGNETIC PULSE (EMP) ATTACK

RISK-BASED NATIONAL INFRASTRUCTURE PROTECTION PRIORITIES FOR EMP AND SOLAR STORMS

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Acronyms and Abbreviations

EMP	electromagnetic pulse
GMD	geomagnetic disturbances
GPS	global positioning system
HF	high frequency
MHD	magnetohydrodynamic
MOV	metal-oxide varistor
UHF	ultra high frequency
VHF	very high frequency

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Introduction

The Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack has provided a compelling case for protecting civilian infrastructure against the effects of EMP and geomagnetic disturbances (GMDs) caused by severe solar storms. Similar to protecting critical infrastructure against any hazard, it will be important to take a risk-based priority approach for these two electromagnetic threats, recognizing that it will be fiscally impracticable to protect everything. In this regard, EMP and solar storms are particularly challenging in that they interfere with electrical and electronic data, control, transmission, and communication systems organic to nearly all infrastructures, simultaneously, over wide areas. The affected geographies may be continental in scale. These events thus represent a class of high-consequence disasters that is unique in coverage and ubiquitous system debilitation. Such disasters deserve particular attention with regard to preparedness and recovery since assistance from non-affected regions of the nation could be scarce or nonexistent. At first blush, the problem of where to begin in developing a national protection program seems overwhelming. Despite the challenges posed by such an endeavor, it is the purpose of the present work to suggest that such a program is possible and affordable based on a system priority approach.

Wide-Area Electromagnetic Environments

The nuclear electromagnetic pulse (EMP), results from a detonation high above the tropopause. Solar storm GMDs occur naturally when an intense wave of charged particles from the sun perturbs the earth's magnetic field.

In the case of high altitude nuclear bursts, three main phenomena come into play, each with distinct associated system effects:

§ The first, a "prompt" EMP field, also referred to as E1, is created by gamma ray interaction with stratospheric air molecules. It peaks at tens of kilovolts per meter in a few nanoseconds, and lasts for a few hundred nanoseconds. E1's broad-band power spectrum (frequency content in the 10s – 100s of megahertz) enables it to couple to electrical and electronic systems in general, regardless of the length of their penetrating cables and antenna lines. Induced currents range into the 1000s of amperes. Exposed systems may be upset or permanently damaged.

§ The second phenomenon, late-time EMP, also referred to as magnetohydrodynamic (MHD) EMP or E3, is caused by the distortion of the earth's magnetic field lines due to the expanding nuclear fireball and rising of heated and ionized layers of the ionosphere. The change of the magnetic field at the earth's surface induces currents of 100s-1000s of amperes in long conducting lines (a few kilometers or greater) that damage components of the electric power grid itself as well as connected systems. Long-line communication systems are also affected including copper as well as fiber-optic lines with repeaters. Transoceanic cables are a prime example of the latter.

§ The third phenomenon, referred to as the "atmospheric effect" is caused by ionization of the upper atmosphere leading to interference with normal radio wave propagation and reflection behavior. The interference last for tens of hours and is most pronounced in the HF, VHF, UHF and GPS transmission bands.

Solar storm GMD effects are the result of large excursions in the flux levels of charged particles from the Sun and their interactions with the Earth's magnetic field and upper atmosphere. Two effects are present:

- Perturbation of the Earth's magnetic field, similar to MHD EMP, that generates overvoltages in long-line systems over large regions of the earth's surface affecting electric power and communication transmission networks.
- Ionization of the upper atmosphere, similar to MHD EMP, leading to interference with high frequency (HF), very high frequency (VHF), ultra high frequency (UHF), and global positioning system (GPS) signals. For typical solar storms, these effects last for around 30 hours.

Wide-Area Electromagnetic Infrastructure Effects

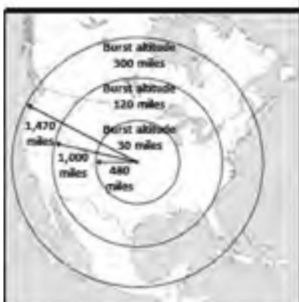
Wide-area electromagnetic system effects are challenging due to their near-simultaneous initial effects and cascading effects on a wide array of infrastructures. Infrastructure systems comprised of long-line conductor networks are the most vulnerable to both effects. Susceptible networks include the electric power grid, land-line communications, and interstate pipelines. Effects on these networks will cascade to most other infrastructures. Smaller, self-contained, self-powered infrastructure systems (e.g. hand-held radios and vehicles) are also vulnerable, but only to EMP and to a lesser degree than long-line networks.

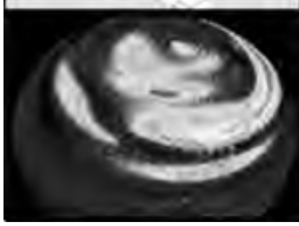
Figure 1 provides a summary of the environments, initially-affected systems and effect longevity. Note that significant synergies exist between the high altitude nuclear burst and solar tsunami geomagnetic and ionospheric environments and system effects. Properly designed high-altitude burst protection measures will suffice against solar storms. The converse is not true, due to the E1 effect.

The Congressional EMP Commission has made a compelling case for protection of critical infrastructure.[1] Its conclusions and recommendations apply to both nuclear and solar effects. However, because their charter forced a broad approach, the Commission wrestled with focus. While recognizing the impossibility of protecting all exposed critical infrastructures, the Commission report was not prescriptive in terms of protection priorities. One reason why a U.S. protection program has yet to be initiated is that policy makers continue to wrestle with the question of where to begin, given the long list of critical infrastructure sectors, viz. Agriculture and Food, Water, Public Health, Energy, Transportation, Banking and Finance, Chemical Industry, Emergency Services, Information and Communication, Postal and Shipping, Government Services, the Defense Industrial Base, and Critical Manufacturing.

EMP and Solar Storm Risks

The Department of Homeland Security (DHS) is pursuing a "risk-based" prioritization approach in developing general protection programs. Such an approach is helpful in developing an EMP/Solar Storm threat protection program as well. A commonly used equation for calculating risk is:





THREAT	Environments	Susceptible Systems	Effects/ Duration
High Altitude Nuclear Burst	Gamma-induced EMP (E1)	All electrical, electronic systems	Component damage / indefinite
	Magnetohydrodynamic (MHD) EMP (E3)	Long-line network systems, e.g., electric power grid, terrestrial comm. lines, pipelines	Component damage / indefinite
	Ionosphere electrical properties perturbation	Radio communication systems and GPS	Wave path degradation / 10s of hours
Solar Tsunamis	Geomagnetic perturbation (GMP)	Long-line network systems, e.g., electric power grid, terrestrial comm. lines, pipelines	Component damage / indefinite
	Ionosphere electrical properties perturbation	Radio communication systems and GPS	Wave path degradation / 10s of hours

Figure 1 Wide-Area Electromagnetic Effects

1 W. Graham et al., Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, Volume 1: Executive Report, 2004.

$$\text{Risk} = E \cdot V \cdot C$$

where E represents probability of system exposure to the threat, V represents system vulnerability, and C represents system criticality. The EMP/solar storm 'exposure factor' is similar for all civilian infrastructures due to the effects' seamless continental-scale coverage. Thus, for the wide-area electromagnetic threats, the equation is simplified because 'vulnerability' and 'criticality' are the sole determinant factors for risk.

A simple risk-based prioritization exercise conducted by the author is instructive using the following vulnerability and criticality criteria:

§ EMP/Solar Storm Vulnerability Criteria (V)

- Does the infrastructure function require connection to long conducting lines and/or networks?
- Does the infrastructure depend on digital electronic control systems?
- Are manual work-around procedures available to perform the infrastructure's function?
- What is the time needed to reconstitute the system?
- How difficult is it to protect the system?

§ EMP/Solar Storm Criticality Criteria (C)

- How many other infrastructures would fail should this infrastructure be debilitated?
- What is the immediacy of effects on services provided?
- How many human casualties would occur?
- How big is the economic impact?
- Is this infrastructure necessary to enable the repair and recovery of other infrastructures post-attack?

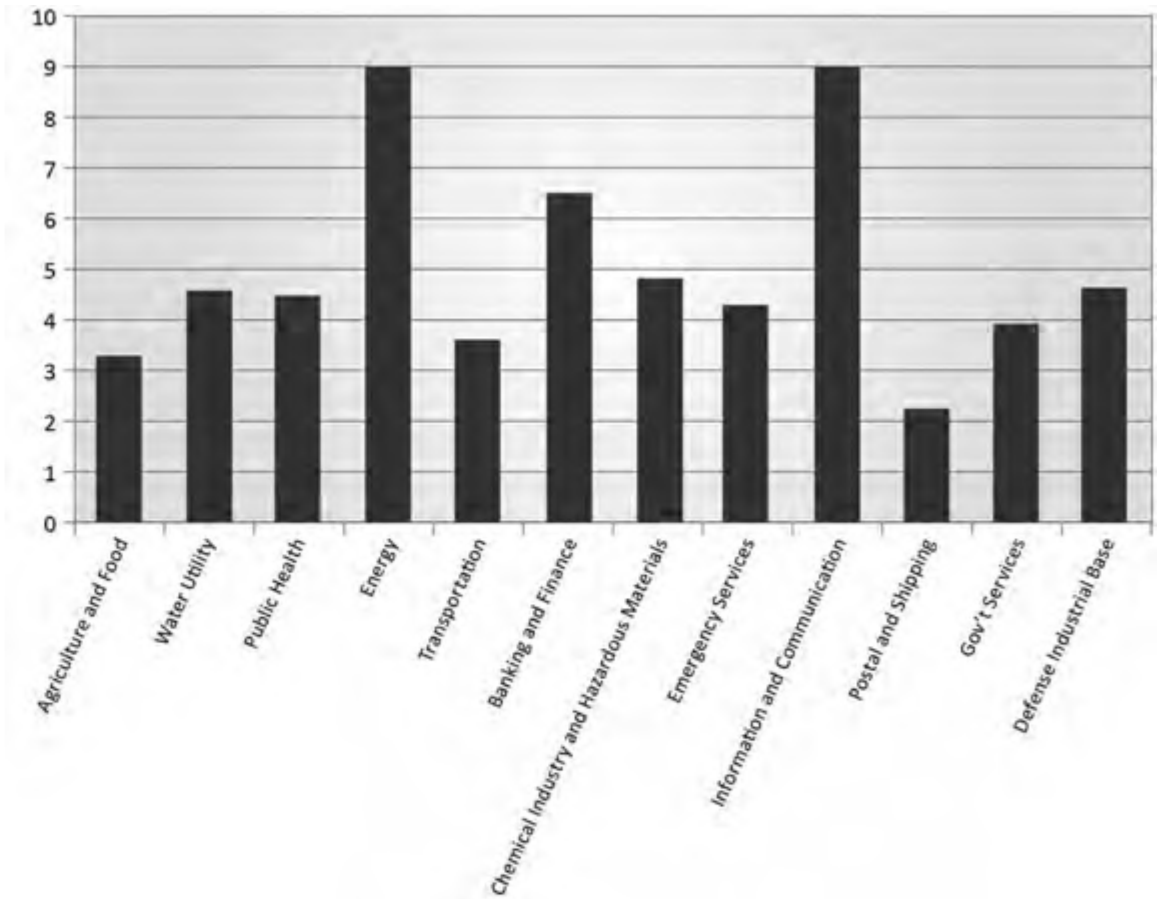


Figure 2 EMP/Solar Storm Risk-Priority Values for Critical Infrastructures

The exercise used a scale of 1 to 3 to score the overall vulnerability and criticality of each infrastructure sector, with 3 being the most vulnerable or critical and 1 being the least. The risk product values thus ranged from 1 to 9. Figure 2 plots the results.

The electric power portion of the energy infrastructure and the information/ communication infrastructure pose the highest risks to society in EMP/Solar Storm scenarios. These infrastructures are the most vulnerable to the wide-area electromagnetic threats due to their organic long-line networks and large associated coupling cross sections. They are the most critical because they enable the operation of all other infrastructures and they are essential with respect to the reconstitution timeline. A profound result of this simple exercise is that our most critical infrastructures are also the most vulnerable to EMP/Solar Storm threats. This conclusion adds impetus for action to protect our electric power and information/communication networks.

Countermeasures

By way of encouragement, we know how to protect systems against wide-area electromagnetic effects. EMP protection has been implemented and standardized by the U.S. Department of Defense on a host of systems. Because of their northerly latitudes, the electric industry in Great Britain, Canada, and the Scandinavian countries have experienced severe solar storm effects and have developed countermeasures that appear to be effective.

Recognizing that significant portions of the U.S. grid are likely to fail in an EMP or major solar storm event, it will be important to expand provision of back-up power systems for basic life functions. This is a lesson learned from our Hurricane Katrina experience now emphasized by LTG Russel Honoré.[2] Many medical, communication, and financial facilities now have emergency generators. Additional provision of emergency generators is needed for water supply systems, gas stations, food stores, and pharmacies. Emergency generators' protection is relatively easy to implement and certify via test.

We have empirical evidence that EMP and solar storm currents damage transformers within the electric grid. These components are expensive, difficult to move, and the largest of transformers are no longer manufactured in the U.S., requiring months to years to replace. Installation of blocking devices in the neutral to ground connections of transformers will significantly reduce the probability of damage from solar storms and MHD EMP. E1 overvoltage protection is achievable by installing common metal-oxide varistors (MOVs) on transformer terminals. Estimates for protecting the most difficult to replace transformers (transmission grid transformers) in the U.S. range $1 to $10 billion.

EMP protection methods for communication facilities have been developed and implemented by DoD since the 1960s and are well documented.[3] Techniques are applicable for both telecommunications facilities and power grid supervisory control and data acquisition (SCADA) systems. Engineering approaches include use of shielded enclosures, provision of backup power, standard grounding techniques, installation of overvoltage protection devices and filters on penetrating conductors, and intentional cable management. The cost of EMP protection for communication facilities ranges 2 to 5 percent of the building costs if incorporated in the initial facility design. Emergency communication facilities are a good place to start to demonstrate the feasibility and cost-effectiveness of electromagnetic protection. Including EMP/solar storm protection in fire codes and interoperable communication system procurements and related DHS grants would be helpful.[4]

Summary and Future Directions

The huge geographic coverage and ubiquitous system effects of EMP and major solar storms beg the question of "where to begin?" a national protection program. We must be clever in deciding where to invest limited resources. Based on simple risk analysis, the electric power and

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2 G. Baker and C. Elliott, editors. Cascading Infrastructure Failures: Avoidance and response, Homeland Security Symposium Proceedings, James Madison University and Federal Facilities Council, May 16, 2007, pp. 19-31.

3 High Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based C^4I Facilities Performing Critical, Time-Urgent Missions, MIL-STD-188-125-1, Fixed Facilities, April 7, 2005 and MIL-STD-188-125-2, Transportable Facilities, March 3, 1999; also MIL-HDBK-423.

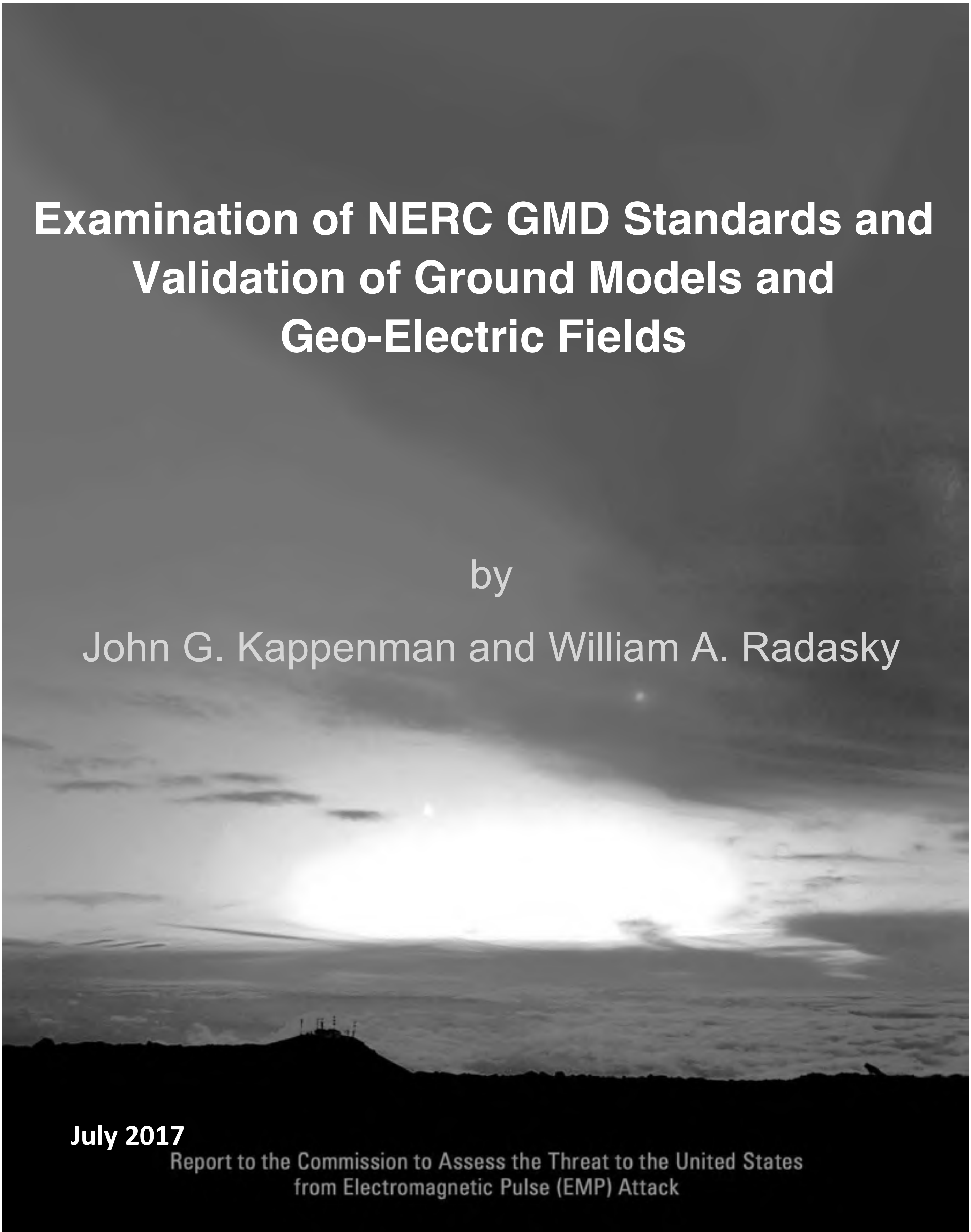
4 See National Fire Protection Association. NFPA 1221, "Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems," and NFPA 1600, "Standard on Disaster/Emergency Management and Business Continuity/Continuity of Operations Programs."

communication infrastructures emerge as both the most vulnerable to EMP and the most critical infrastructures, and thus the highest priority for EMP/solar storm protection. Protection of a limited set of high risk infrastructures will go a long way in lessening the societal impact. In the case of electric power, protecting the large distribution transformers and expanding the provision of emergency generators for critical systems will improve the survivability of multiple other interdependent infrastructures. For communication systems, protection of emergency communication centers and interoperable mobile and handheld communication systems are useful first steps. Pilot programs to demonstrate wide-area EM protection engineering for the highest risk infrastructures would pave the way for a comprehensive effort to address critical national infrastructures. Recent Congressional, FERC, and NERC initiatives will hopefully spur progress in this direction.[5,6,7]

5 H.R. 668, the Secure High Secure High-voltage Infrastructure for Electricity from Lethal Damage (SHIELD) Act, introduced February 16, 2011.

6 U.S. Department of Energy and the North American Electric Reliability Corporation. *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System: A jointly-commissioned summary report of the North American Electric Reliability Corporation and the U.S. Department of Energy's November 2009 Workshop*, June 2010.

7 National Academies Press. *Severe Space Weather Events: Understanding societal and economic impacts: A workshop report*, 2008.



Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields

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John G. Kappenman and William A. Radasky

July 2017

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By
John G. Kappenman, Storm Analysis Consultants
William A. Radasky, Metatech Corporation

July 2017

ACRONYMS AND ABBREVIATIONS

BPA	Bonneville Power Authority
EMP	electromagnetic pulse
GIC	geomagnetically induced currents
NERC	North American Electric Reliability Corporation
GMD	geomagnetic disturbance
FERC	U.S. Federal Energy Regulatory Commission
SWPC	Space Weather Prediction Center
CCMC	Community Coordinated Modeling Center
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
FOIA	Freedom of Information Act
NRCan	Natural Resources Canada

PREFACE

This analysis of the U.S. electric power grid vulnerability to geomagnetic storms was originally conducted as part of the work performed by Metatech Corporation for the Congressional appointed U.S. EMP Commission, which started their investigations in late 2001. Subsequent work performed for the U.S. Federal Energy Regulatory Commission (FERC) was released in a detailed report in 2010, entitled, "Geomagnetic Storms and Their Impacts on the U.S. Power Grid," by J.G. Kappenman. In that report, models to calculate the geomagnetically induced currents (GICs) in high voltage power grids from geomagnetic storms were developed and validated—using data from previous storms—to ensure their accuracy. In October 2012, the FERC ordered the U.S. electric power industry via their standards development organization, North American Reliability Corporation (NERC), to develop new standards addressing the impacts of a geomagnetic disturbance to the bulk electric power grid. While the standard was in draft, Kappenman and Radasky assessed the work performed by NERC to develop the standard including the specification of geo-electric fields. This staff paper is the result of that assessment. The draft standard was approved by FERC in September 2016 as *Reliability Standard-TPL-007-1: Transmission System Planned Performance for Geomagnetic Disturbance (GMD) Events*.

The following key points highlight the importance of this assessment:

§ Using available GIC measurements, geo-electric fields over mesoscale regions can be characterized and the accuracy of the measurements can be assessed using Ohm's Law. This methodology provides a strict constraint on the minimum geo-electric field level during a storm event.

§ Comparison of actual geo-electric fields with the fields derived by the NERC model show a systematic underprediction of the geo-electric field by the NERC model. In the cases examined, this underprediction is a particular problem in estimating the rapid rates of change in the geomagnetic field during the most important portions of the storm events. This underprediction produces erroneous geo-electric field intensity estimates that are too low by a factor of ~2, and may be too low by a factor of 5 or more.

§ These errors call into question many of the foundational findings in the NERC standard for GMD. The flawed geo-electric field model was used to develop the peak geo-electric field levels of the benchmark model proposed in the standard. Because this model understates the geo-electric field intensity for small storms by at least a factor of two, it would also understate the maximum geo-electric field by similar or even larger levels. These flaws are entirely integrated into the NERC standard and as a result, the directives in the standard are not valid.

It is crucial that the NERC standard methodology and the standard itself be corrected through a process of model validation with comparisons with actual data. This staff paper provides a clear guide as to how to use such data to evaluate the accuracy of geomagnetic storm modeling in developing a GMD standard for protecting high voltage power grids.

Executive Summary

The analysis of the US electric power grid vulnerability to geomagnetic storms was originally conducted as part of the work performed by Metatech Corporation for the Congressional Appointed US EMP Commission, which started their investigations in late 2001. In subsequent work performed for the US Federal Energy Regulatory Commission, a detailed report was released in 2010 of the findings[11]. In October 2012, the FERC ordered the US electric power industry via their standards development organization NERC to develop new standards addressing the impacts of a geomagnetic disturbance to the electric power grid. NERC has now developed a draft standard and has provided limited details on the technical justifications for these standards in a recent NERC White Paper[22].

The most important purpose of design standards is to protect society from the consequences of impacts to vulnerable and critical systems important to society. To perform this function the standards must accurately describe the environment. Such environment design standards are used in all aspects of society to protect against severe excursions of nature that could impact vulnerable systems: floods, hurricanes, fire codes, etc., are relevant examples. In this case, an accurate characterization of the extremes of the geomagnetic storm environment needs to be provided so that power system vulnerabilities against these environments can be accurately assessed. A level that is arbitrarily too low would not allow proper assessment of vulnerability and ultimately would lead to inadequate safeguards that could pose broad consequences to society.

However from our initial reviews of the NERC Draft Standard, the concern was that the levels suggested by NERC were unusually low compared to both recorded disturbances as well as from prior studies. Therefore this white paper will provide a more rigorous review of the NERC benchmark levels. NERC had noted that model validations were not undertaken because direct measurements of geo-electric fields had not been routinely performed anyway in the US. In contrast, Metatech had performed extensive geo-electric field measurement campaigns over decades for storms in Northern Minnesota and had developed validated models for many locations across the US in the course of prior investigations of US power grid vulnerability[3]. Further, various independent observers to the NERC GMD tasks force meetings had urged NERC to collect decades of GIC observations performed by EPRI and independently by power companies as these data could be readily converted to geo-electric fields via simple techniques to provide the basis for validation studies across the US. None of these actions were taken by the NERC GMD Task Force.

It needs to be pointed out that GIC measurements are important witnesses and their evidence is not being considered by the NERC GMD Task Force in the development of these standards. GIC observations provide direct evidence of all of the uncertain and variable parameters including the deep Earth ground to the driving geomagnetic disturbance environment. Because the GIC measurement response is also obtained from the power grid itself, it incorporates all of the meso-scale coupling of the disturbance environments to the assets themselves and the overlying circuit topology that needs

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1 *Geomagnetic Storms and Their Impacts on the U.S. Power Grid* (**Meta-R-319**), John Kappenman, Metatech Corporation, January 2010. Via weblink from Oak Ridge National Lab, *wttp://www.ornl.gov/sci/ees/etsd/pes/ferc_emp_gic.shtml*

2 NERC Benchmark Geomagnetic Disturbance Event Description, *http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/Benchmark_GMD_Event_April21_2.pdf*

3 Radasky, W. A., M. A. Messier, J. G. Kappenman, S. Norr and R. Parenteau, "Presentation and Analysis of Geomagnetic Storm Signals at High Data Rates", IEEE International Symposium on EMC, August 1993, pp. 156-157.

to be assessed. Separate discreet measurements of geo-electric fields are usually done over short baseline asset arrays which may not accurately characterize the real meso-scale interdependencies that need to be understood. The only challenge is to interpret what the GIC measurement is attempting to tell us, and fortunately this can be readily revealed with only a rudimentary understanding of Ohm's Law, geometry and circuit analysis methods, a tool set that are common electrical engineering techniques. Essentially the problem reduces to: *"if we know the I (or GIC) and we know the R and topology of the circuit, then Ohm's law tells us what the V or geo-electric field was that created that GIC"*. Further since we know the resistance and locations of power system assets with high accuracy, we can also derive the geo-electric field with equally high certainty. These techniques allow superior characterization of deep Earth ground response and can be done immediately across much of the US if GIC measurements were made available. Further these deep Earth ground responses are based upon geological processes and do not change rapidly over time. Therefore even measurements from one storm event can characterize a region. Hence this is a powerful tool for improving the accuracy of models and allows for the development of accurate forward looking standards that are needed to evaluate to high storm intensity levels that have not been measured or yet experienced on present day power grids.

Unfortunately this tool has not been utilized by any of the participants in the NERC Standard development process.

It has been noted that the NERC GMD Task Force has adopted geo-electric field modelling techniques that have been previously developed at FMI and are now utilized at NRCan. The same FMI techniques were also integrated into the NASA-CCMC modeling environments and that as development and testing of US physiographic regional ground models were developed, efforts were also undertaken by the USGS and the NOAA SWPC to make sure their geo-electric field models were fully harmonized and able to produce uniform results. However, it appears that none of these organizations really did any analysis to determine if the results being produced were at all accurate in the first place. For example when recently inquired, NRCan indicated they will perhaps begin capturing geo-electric field measurements later this year to validate the base NERC Shield region ground model, a model which provides a conversion for all other ground models. In looking at prior publications of the geo-electric field model carried out in other world locations, it was apparent that the model was greatly and uniformly under- predicting for intense portions of the storms, which are the most important parameters that need to be accurately understood.

In order to examine this more fully, this white paper will provide the results of our recent independent assessment of the NERC geo-electric field and ground models and the draft standard that flows from this foundation. Our findings can be concisely summarized as follows:

- Using the very limited but publicly available GIC measurements, it can be shown how important geo-electric fields over meso-scale regions can be characterized and that these measurements can be accurately assessed using the certainty of Ohm's Law. This provides a very strict constraint on what the minimum geo-electric field levels are during a storm event.

- When comparing these actual geo-electric fields with NERC model derived geo-electric fields, the comparisons show a systematic under-prediction in all cases of the geo-electric field by the NERC model. In the cases examined, the under prediction is particularly a problem for the rapid rates of change of the geomagnetic field (the most important portions of the storm events) and produce errors that range from factor of ~2 to over factor of ~5 understatement of intensity by the NERC models compared to actual geo-electric field measurements. These are enormous errors and are not at all suitable to attempt to embed into Federally-approved design standards.

- These enormous model errors also call into question many of the foundation findings of the NERC GMD draft standard. The flawed geo-electric field model was used to develop the peak geo-electric field levels of the Benchmark model proposed in the standard. Since this model understates the actual geo-electric field intensity for small storms by a factor of 2 to 5, it would also understate the maximum geo-electric field by similar or perhaps even larger levels. Therefore this flaw is entirely integrated into the NERC Draft Standard and its resulting directives are not valid and need to be corrected.

The findings here are also not simply a matter of whether the NERC model agrees with the results of the Metatech model. Rather the important issue is the degree that the NERC model disagrees with actual geo-electric field measurements from actual storm events. These actual measurements are also confirmed within very strict tolerances via Ohm's Law, a fundamental law of nature. The results that the NERC model has provided are not reliable, and efforts by NERC to convince otherwise and that utilization of GIC data cannot be done are simply misplaced. Actual data provides an ultimate check on unverified models and can be more effectively utilized to guide standard development than models because as Richard Feynman once noted; "Nature cannot be fooled"!

Introduction to NERC Model Evaluation and Validation Overview

A series of case study examples will be provided in this White Paper to illustrate the evaluation of geo-electric fields derived from GIC measurements across the US electric power grid. These derived geo-electric field results will then be compared to the NERC estimated geo-electric fields for the same storm events and scenarios. There are an important number of underlying principles to this analysis that can be summarized as follows:

- Using past storms and by modeling detailed power networks and comparing to GIC measurements at particular locations is the best way to validate overall storm-phenomena/power grid models. It accounts for the "interpolation" of the incident measured B-fields (including the angular rotation of the fields with time), the accuracy of the ground model used, the coupling to the power network, and the computation of the current flow at the measurement point.

- Experience has shown that over times of minutes, the geomagnetic field will rotate its direction and therefore every transformer in a network will have a sensitivity to particular vector orientations of the field, and the maximum current measured at a given transformer location will be a function of the rate of change intensity of the geomagnetic field, the resulting geo-electric field this causes and the angle of the field as it changes over the storm event. This is why the rate of change (dB/dt) and GIC at a single transformer will not scale perfectly with the maximum value of dB/dt, but taking into consideration all of these topology and orientation factors, a highly accurate forensic analysis can be performed.

- Geomagnetic storms are not steady state events, rather they are events with aperiodic extreme impulsive disturbances that can occur over many hours or days duration. Modeling these events to derive a geo-electric field is challenging but readily achievable. Since these events are time domain problems, modeling solutions using time-domain methods are recommended. The NERC modeling methods that will be evaluated here have generally been developed using Fourier transform frequency domain methods. In these implementations of Fourier methods, the primary question is the accuracy in dealing with the phase of the Fourier transforms.

- When referring to impulsive geomagnetic field disturbance events, these are typically multiple discrete events with times of several minutes. Note that the collapse of the Quebec power network in March 1989 occurred in 93 seconds. Clearly times of only a few minutes are important and it is vital that the geo-electric field intensity of these transients be accurately portrayed and not understated in a Design Standard type document. For example, a 10 meter dyke defined by the standard does no good, if the actual Tsunami height is 15 meters. Any efforts to claim that models that depict some satisfactory averaging over extended time periods as being sufficient must be vigorously refuted, as these peak inflection points are the most vital aspects of the storm environments that must be accurately determined.

Simulation Model Validation – Maine Grid Examples

In the analysis carried out for the FERC Meta-R-319 report, extensive efforts were undertaken to verify that the simulation models for the US power grid were providing sufficiently accurate results. One of the primary approaches that were utilized to test these models were to perform simulations for forensic analysis purposes and to compare the results with discrete measurements that were available.

One of the forensic simulations was conducted on the Maine grid and provided important verification of the ability of the model in that portion of the US grid to produce accurate estimates. Figure 1 provides a plot of the results of this simulation showing the "Calculated" versus "Measured" GIC (geomagnetically induced current) at the Chester Maine 345kV transformer. This was for a storm which occurred on May 4, 1998 and was driven by the large scale storm conditions as shown in Figure 2.

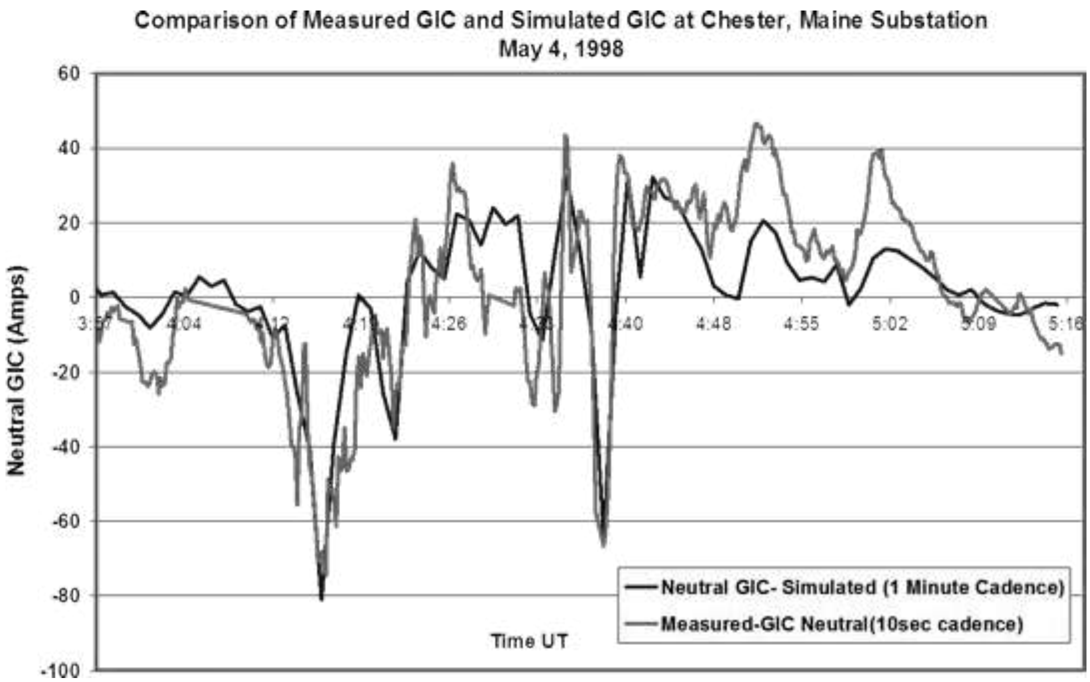


Figure 1 – Plot showing comparison of Simulated versus Measured GIC at Chester Maine 345kV transformer for May 4, 1998 geomagnetic storm. (Source – Meta-R-319)

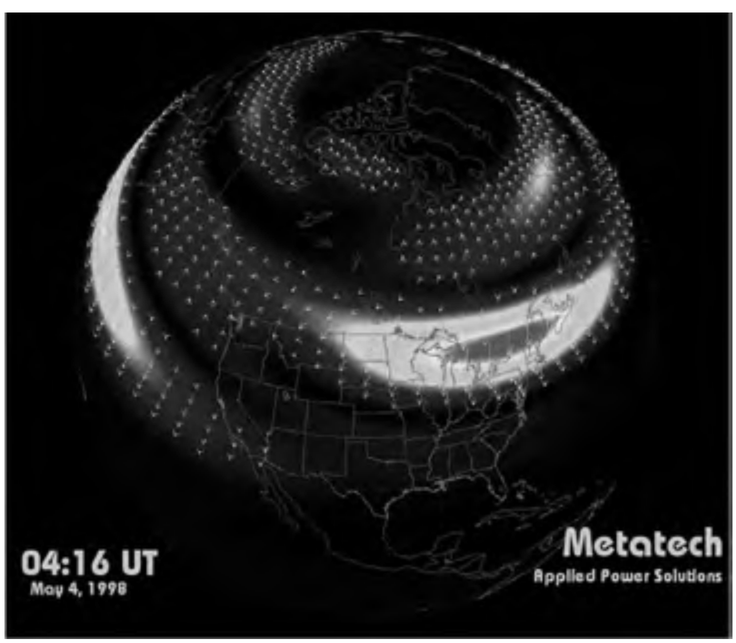


Figure 2 – Map of Geomagnetic Disturbance conditions at 4:16UT during May 4, 1998 storm. (Source – Meta-R-319)

The results in Figure 1 provide a comparison between high sample rate measured GIC (~10 second cadence) versus storm simulations that were limited to 1 minute cadence geomagnetic observatory data inputs (B-fields). Due to this limitation of inputs to the model, the model would not be able to reproduce all of the small scale high frequency variations shown in the measured data. However, the simulation does provide very good accuracy and agreement on major spikes in GIC observed, the most important portion of the simulation results that need to be validated. Figure 3 provides a wider view of the impact of the storm in terms of other GIC flow conditions in the Maine and New England region electric power grid, this is provided at time 4:16UT.

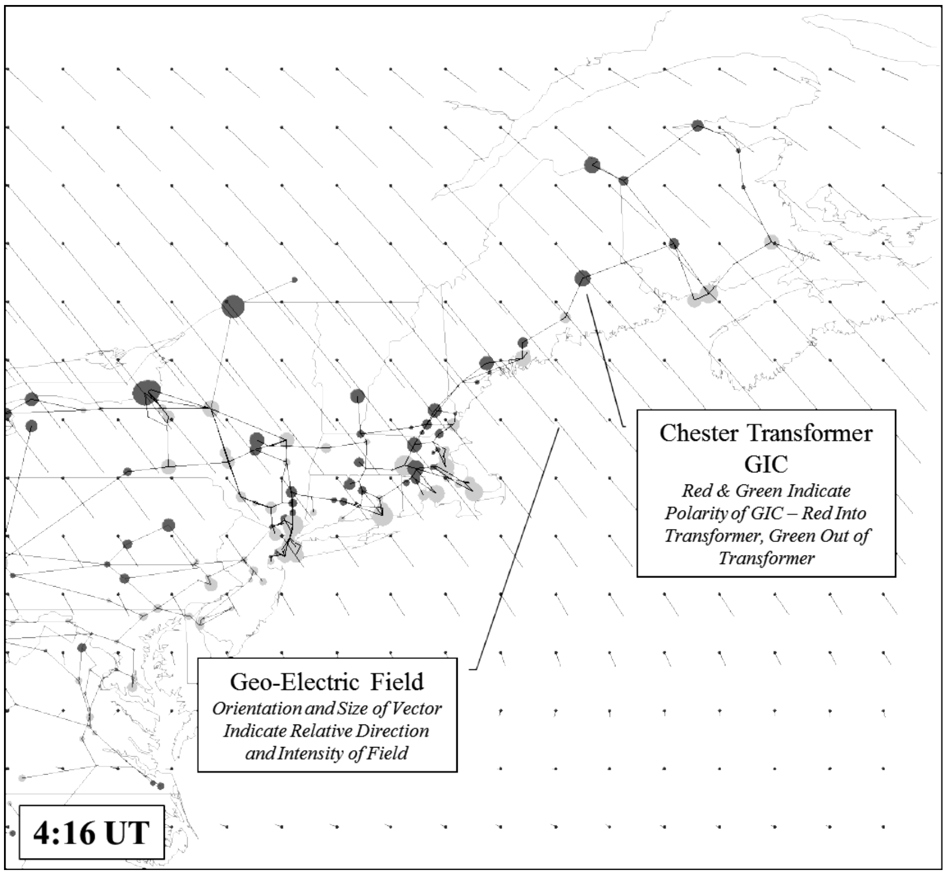


Figure 3 – GIC flows and disturbance conditions in Maine/New England grid at 4:16UT, May 4, 1998. (Source – Meta-R-319)

As this illustration shows, the Chester GIC flow is shown along with comparable GIC flows in a number of other locations in the regional power grid at one minute in time. In addition to impacts to the New England grid, extensive power system impacts were also observed to voltage regulation in upstate New York region due to storm. In this map, the intensity and polarity of GIC flows are depicted by red or green balls and their size, the larger the ball the larger the GIC flow and the danger it presents to the transformer and grid. Also shown are the blue vector arrows which are the orientation and intensity of the geo-electric field which couples to the topology of the electric grid and produces the GIC flow patterns that develop in the grid. It is noted that during the period of this storm, the electric fields rotated and all transformers in the grid would experience a variation in the pattern of GIC flows.

Considerable scientific and engineering examination has been performed since the release of the Meta-R-319 report; the report and other subsequent examinations are in close agreement on a number of important parameters of future severe geomagnetic storm threat conditions. For example, it is now well-accepted that severe storm intensity disturbance intensity can reach level of 5000 nT/min at the latitudes of the Maine power grid. NRCan now provides estimates of geo-electric fields for the nearby Ottawa observatory for storms including the May 4, 1998 storm. The ability therefore exists to do cross-validations with this and other proposed NERC ground models and geo-electric field calculation methods.

Observations of GIC at the Chester Maine substation also provide important observational confirmations that allow empirical projection of GIC levels that are plausible at more severe storm intensities. Earlier this year, the Maine electric utilities provided a limited summary of peak GIC observations from their Chester transformer and storm dates to the Maine Legislature. Figure 4 provides a graphical summary that was derived of the peak GIC and peak disturbance intensities (in nT/min) observed at the Ottawa Canada geomagnetic observatory for a number of reported events. The Maine utilities did not provide accurate time stamps (just date only), so that limits some of the ability to accurately correlate disturbance intensity to GIC peaks as the knowledge of timing is extremely coarse. Also since the Ottawa observatory is approximately 550km west of Chester, there is some uncertainty to local storm intensity specifics near Chester. However as shown, there are clear trend lines and uncertainty bounding of the level of GIC and how the GIC increases for increasing storm intensity. This trend line is quite revealing even with all of the previously mentioned uncertainties on the spatial and temporal aspects of the threat environments.

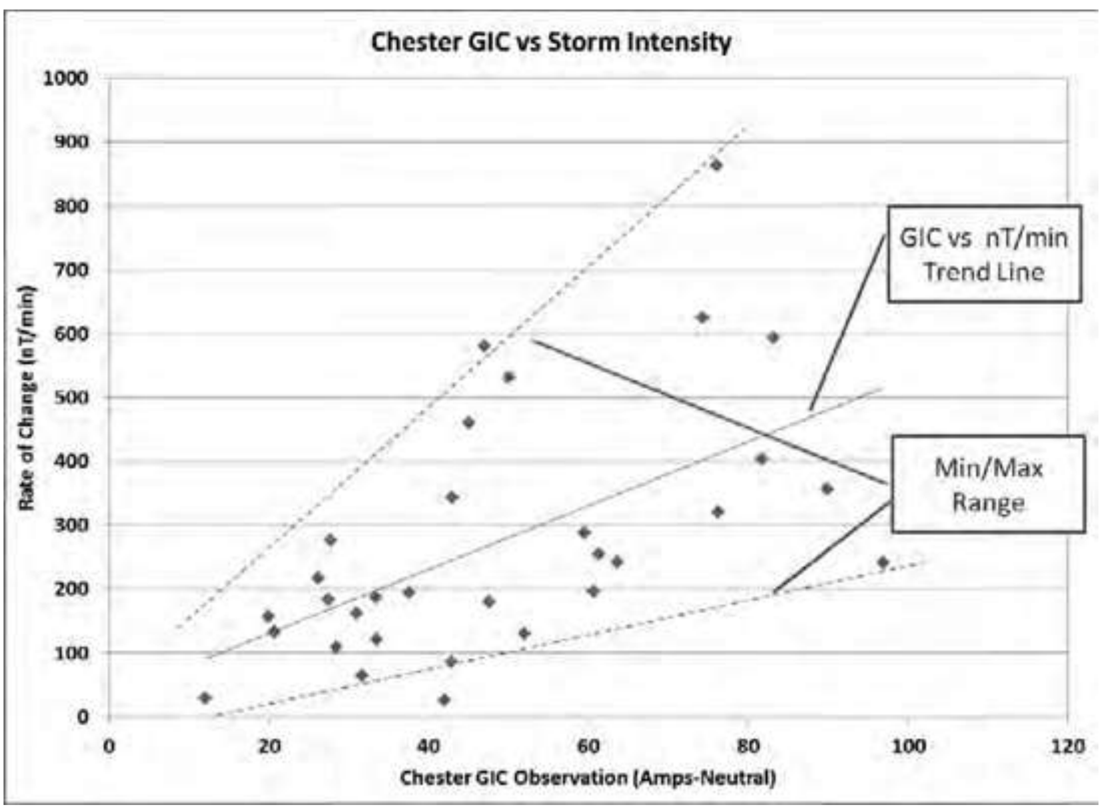


Figure 4 – GIC versus Storm Intensity (nT/min) from multiple observed GIC storm events at Chester Transformer, in this case the GIC timing is extremely coarse.

At higher storm intensities, the geo-electric field increases and if only intensity changes (as opposed to spectral content), then the increase in geo-electric field and resulting GIC will be linear. Because storm intensity for very severe storms can reach ~5000 nT/min, this graph can be linearly extended to project the range of GIC flows in the Chester transformer for these more extreme threat conditions. Figure 5 provides a plot similar to that in Figure 4, only with linear extensions of the GIC flow that this observational data estimates.

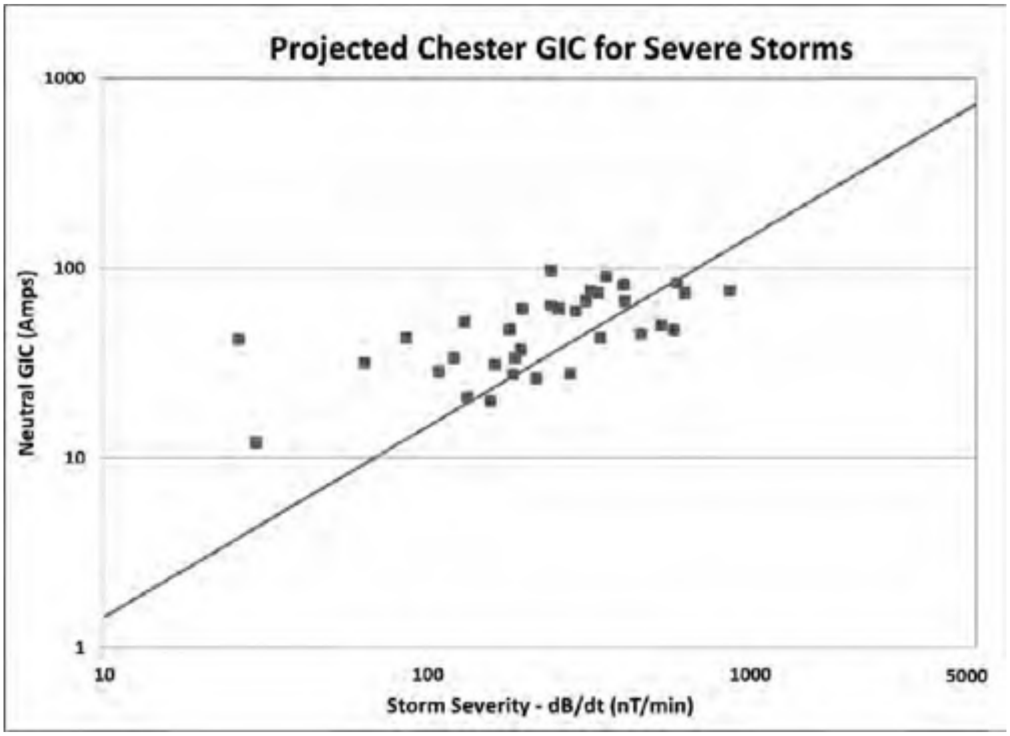


Figure 5 – Projected Chester GIC flow for storm intensity increasing to ~5000 nT/min.

Using these data plotting techniques with the previously noted uncertainties, a more detailed examination can be performed for one of the specific storm events which occurred on May 4, 1998. Figure 6 provides again the earlier described GIC plots from Figure 1. Two particularly important peak times are also highlighted on this plot at 4:16UT and 4:39UT where the recorded GIC reaches peaks respectively of -74.3 Amps and -66.6 Amps. These comparisons also show very close agreement with the simulation model results as well. Therefore the peak data points can be more explicitly examined in detail, as a comparison to how GIC vs dB/dt was plotted in Figure 4. In addition to this GIC observation data, there was also dB/dt data observed from a local magnetometer for this storm, which also greatly reduces the uncertainty of the threat environment.

Having all of this data available will aid in utilizing the power system itself as an antenna that can help resolve the geo-electric field intensity that the complex composition of ground strata generates during this storm event. Further once this response is empirically established, this same ground response can be reliably utilized to project to higher storm intensity and therefore higher GIC levels. This provides a blended effort of model and observational data to extract details on how the same grid and ground strata would behave at higher storm intensity levels. One of the advantages that exists in the modeling of the circuits of the transmission networks are that the resistive impedances of transmission lines and transformers (which are the key GIC flow paths) are very well known and have small uncertainty errors. It is also known that the Chester transformer is non-auto, so GIC flow in the neutral also defines the GIC per phase. There is also no doubt about the locations of assets within the circuit topology. Finally, station grounding resistance can also be determined to relatively high certainty as well. In comparison, ground response as has been previously published in the Meta-R-319 report can vary over large ranges, as much as a factor of 6. Therefore direct observations of ground response are highly important and GIC measurements, as will be discussed, provide an excellent proxy or geophysical data that can be used to derive the complex behavior characteristics of the ground strata. This set of understandings can be applied as a tool to significantly bound this major area of uncertainty.

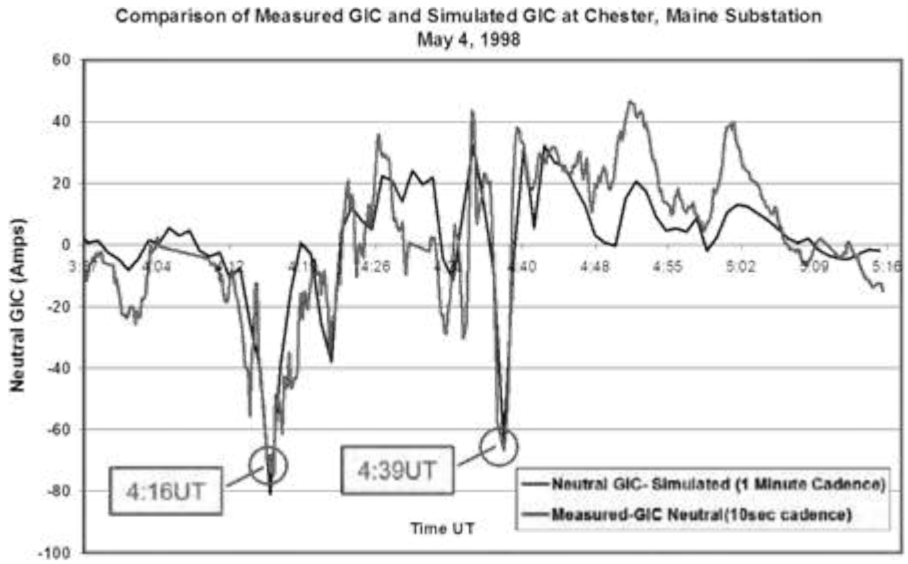


Figure 6 – GIC observation at times 4:16 & 4:39 UT that can be examined in further detail.

Network Model and Calculation of Chester GIC for 1 V/km Geo-Electric Field

Using the Maine region power grid model of the EHV grid, it is possible to examine what the GIC flow would be at the Chester transformer for a specified geo-electric field intensity of 1 V/km. This specified GIC is an intrinsic and precise characteristic of the network that will provide a useful yardstick to calibrate against for actual GIC flows that occurred and from that a more highly bounded geo-electric field intensity range can be determined at this location. Figure 7 provides a plot of the GIC flow in the Chester transformer for a 1 V/km geo-electric field. Since the topology of the transmission network also greatly determines the resulting GIC, this calculation is performed for a full 360 degree rotation of the orientation of the 1 V/km field.

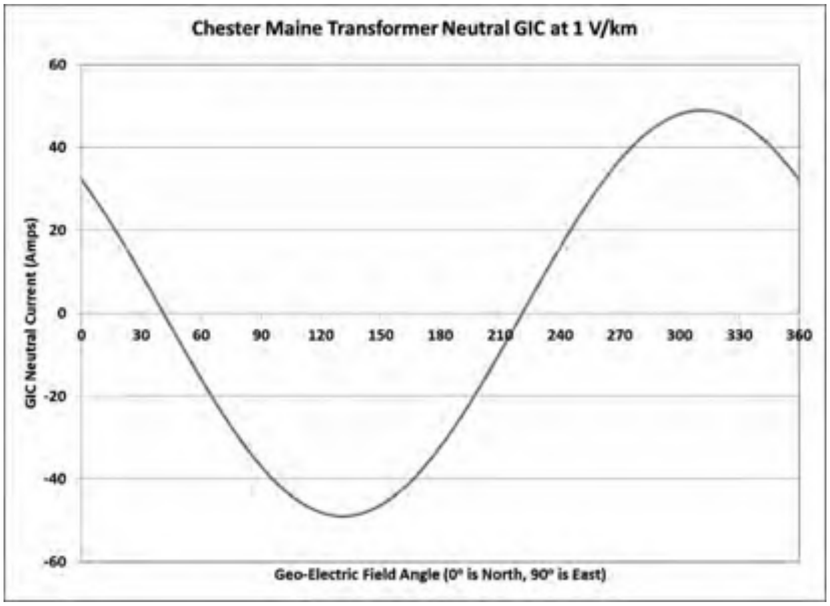


Figure 7 – GIC flow at Chester transformer neutral for 1 V/km geo-electric field at various orientation angles.

As the plot in Figure 7 shows, the peak GIC flow at this location is ~49 Amps which occurs at the 130° and 310° angular orientations of the 1 V/km field.

While the GIC to 1 V/km relationship in Figure 7 is developed from a detailed network model, there are also much simpler methods using a limited knowledge of a portion of the local transmission network that can be used to check the accuracy of the model. This involves a simple circuit analysis to derive the resistance and orientation specifics of just the two major transmission lines connecting to Chester. Each of the two 345kV lines connecting to Chester (from Chester-Orrington and from Chester to Keswick New Brunswick) is shown in the map of Figure 8.

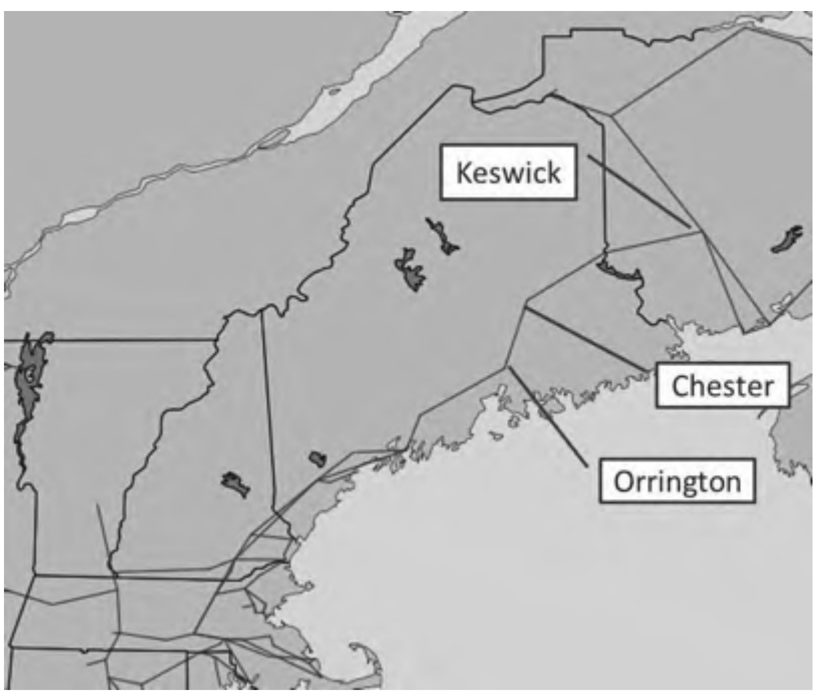


Figure 8 - Map of Chester Maine and 345kV line interconnections.

For geomagnetic storms, the orientation of specific transmission lines becomes very important in determining their coupling to the geo-electric field which also has a specific orientation. For example if the orientation of a specific line is identical to the orientation of the geo-electric field, then the GIC will be at a relative maximum. Conversely if the orientations of the field and line are orthogonal, then no coupling or GIC flow will occur. In the case of the Chester to Keswick line, the orientation is at an angle of ~70^{o} (with 0^{o} being North) and for the Chester to Orrington line the angle is ~205^{o}. Hence it should be expected that each line will couple differently as the orientation of the geo-electric field changes. Also an important parameter in the calculation of GIC is the line length which also describes the total resistance of this element of the GIC circuit. The point to point distances from Chester are ~80 km to Orrington and ~146 km to Keswick. Figure 9 provides the results of a simple single circuit calculation of the Chester transformer GIC connected to a 345kV transmission line of variable length with a transformer termination at the remote end of that line, the estimated GIC is also shown for the 80 km Orrington line and the 146 km Keswick line using a uniform 1 V/km geo-electric field strength. As shown in this figure, for the two line lengths only a small change in GIC occurs (~11%), even though there is nearly a factor of two difference in line lengths. This calculation assumes a full coupling with the orientation of the geo-electric field, as the geo-electric field changes its orientation to the line with time, and the GIC will change as prescribed via a sine function.

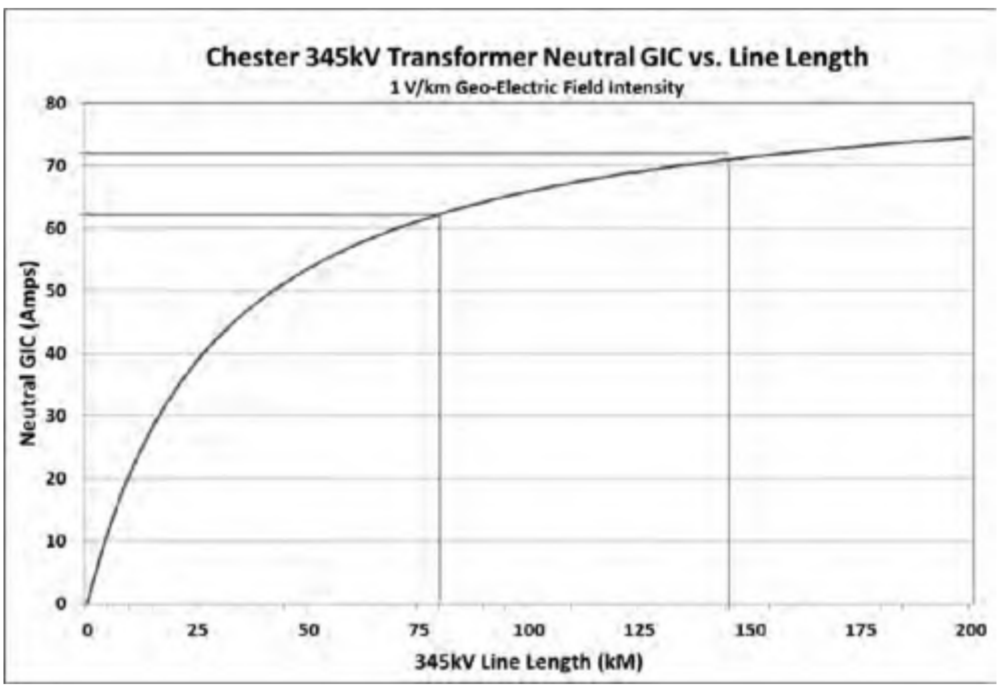


Figure 9 – Calculated Chester GIC for single circuit 345kV transmission line, 80 km Orrington and 146km Keswick noted

Given this simple two line case, a discrete calculation can be performed for each line, and using circuit superposition principles(Kirchoff's Laws), the resulting Chester GIC flow can be plotted as well versus the orientation angle of a uniform 1 V/km geo-electric field. This is shown in Figure 10 for each of the two lines and the resultant GIC flow at Chester.

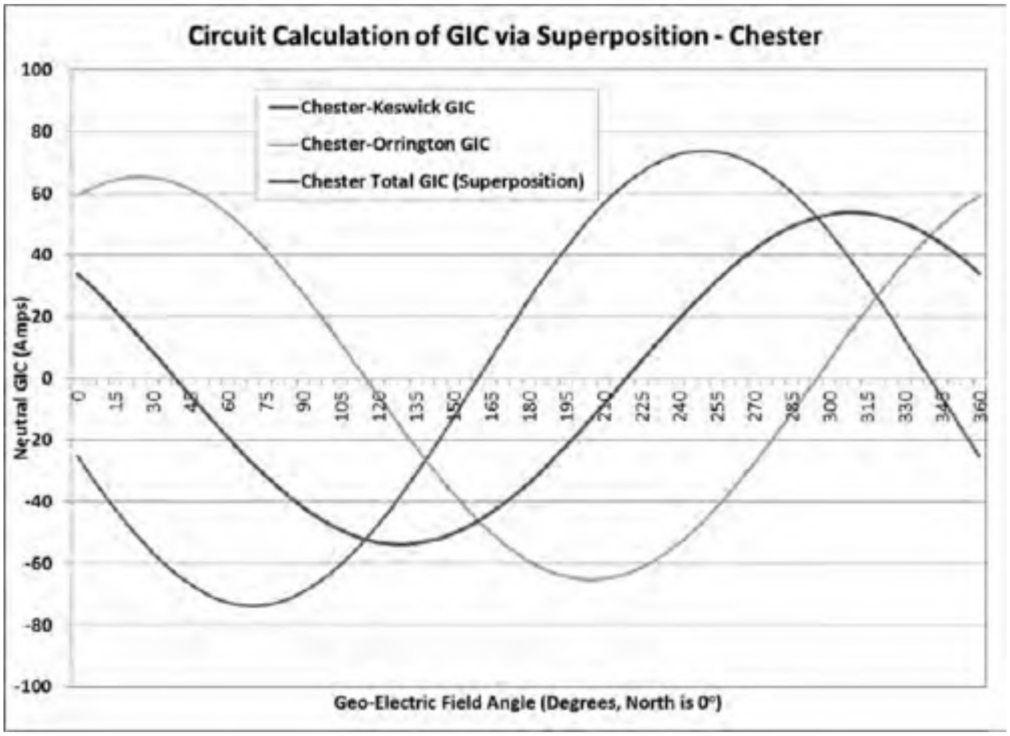


Figure 10 – GIC flow for each line versus geo-electric field angle and Resultant GIC at Chester.

Determining Storm Geo-Electric Field Intensity from Observed GIC

As this Figure 10 illustrates, each line segment will have differing GIC flows versus the orientation of the geo-electric field, and the resultant Chester neutral GIC will also be of lower magnitude and will also have a differing vector angle to each line segment. This simple Ohm's law based circuit calculation can be compared to the more detailed model calculation previously shown in Figure 7, which is shown in Figure 11. As this Figure illustrates, there is very good agreement in GIC flows using the two-line calculation approache (~95% agreement). The detailed model result will be more exact because all of the other network assets are used in the calculation. However, this comparison also shows that the line length parameter dominates the impedance of the circuit and defines the circuit current given the circuit resistances of just a few key components. Knowing both I (or GIC in this case) and R of the circuit allows the ability to precisely determine the driving V or geo-electric field that caused the observed GIC to occur in the transformer.

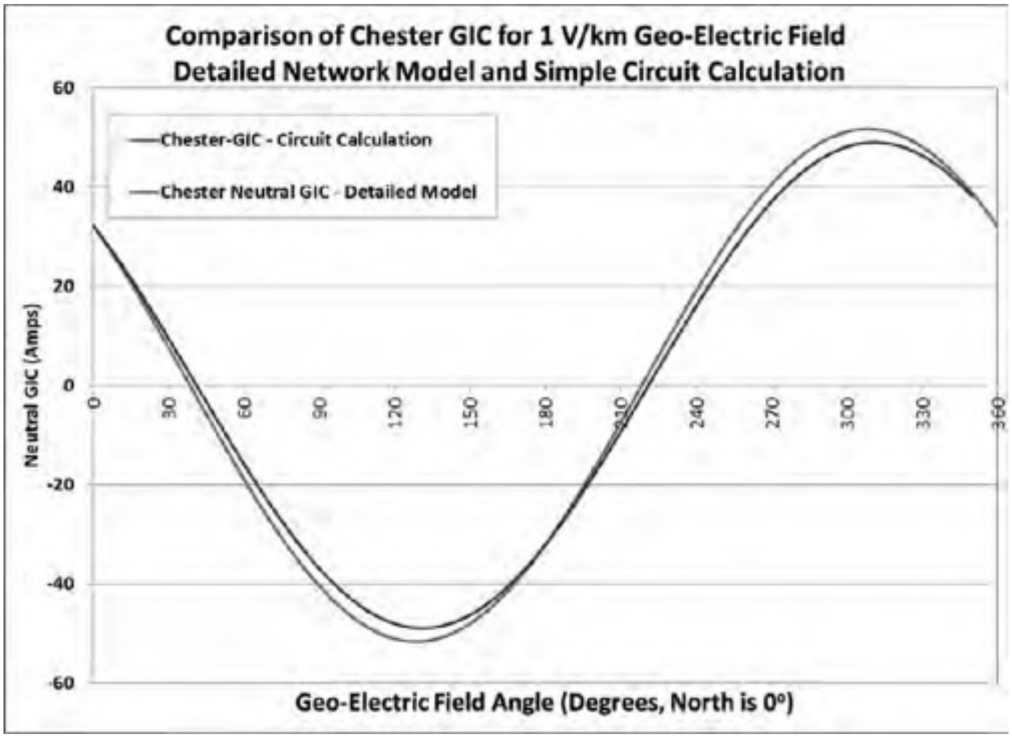


Figure 11 – Comparison of Calculated Chester GIC from detailed model and simple circuit calculation

Using the data from Figures 6 (the observed GIC at Chester) and Figure 11, it can be immediately inferred that the peak GIC levels of -66.6 and -74.3 Amps would have required a geo-electric field intensity of greater than 1 V/km to have occurred to produce such high levels of GIC. This is simply a process of utilizing Ohm's law knowledge to begin to develop an improved understanding of the geo- electric field intensity, an otherwise complex and uncertain field to calculate. In contrast it is not possible to infer the upper bound of geo-electric field, in that at angles where GIC nulls occur (such as 40^{o} and 220^{o}) even with a very high geo-electric field will not produce a significant GIC flow. As this point illustrates, these estimates can also be greatly improved by adding a simple understanding of geometry to this calculation. For example at time 4:16 UT, the simulation model results shown previously in Figure 3 illustrates a geo-electric field orientation at the Chester location which is almost exactly at 130^{o}, the orientation that would produce a peak GIC response at Chester. Using this circuit relationship of current to voltage allows extension to a scaling of the 49 Amp GIC at 1 V/km to a field intensity that would instead result in a 74.3 Amps GIC magnitude. This would lead to the estimated geo- electric field intensity at this 4:16UT time of ~1.5 V/km.

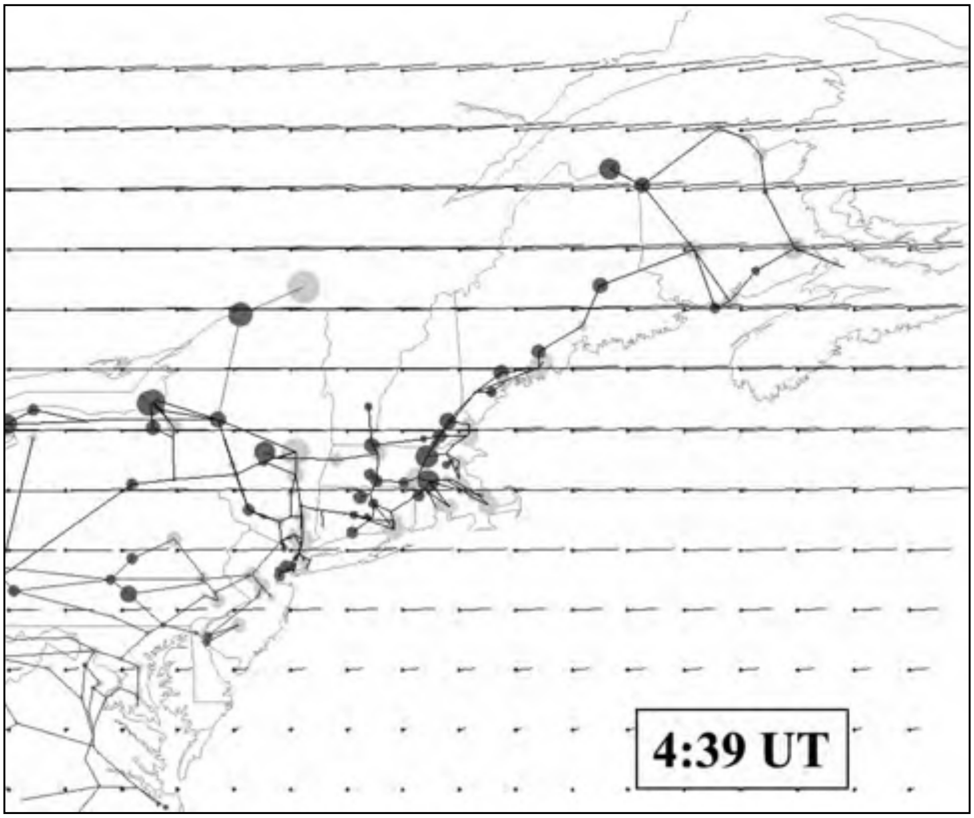


Figure 12 - GIC flows and disturbance conditions in Maine/New England grid at 4:39UT, May 4, 1998.

A similar simplified empirical analysis to confirm model results and expected geo-electric field levels can also be performed at time 4:39UT. Figure 12 provides a simulation output at time 4:39UT which again shows the intensity and geo-electric field angular orientation that would have occurred at this time step. This shows that the field was Eastward oriented or ~90°. Since the characteristic GIC flows at Chester behave as a sine wave for variation of the geo-electric field angle to these circuit assets, a scaling factor based on these angular characteristics can also be applied, which would rerate the field to account for the less-optimal orientation angle at this time. In this case, the 66.6 Amp GIC would be produced by total geo-electric field of ~2 V/km, but only ~1.4 V/km of this total geo-electric field is utilized to produce a GIC flow in the Chester transformer. As this case illustrates, a higher total geo-electric field intensity occurred at 4:39UT than at time 4:16 UT, even though the GIC is lower at 4:39UT. This appears to be counter intuitive. However the event produced a smaller GIC, with the important difference being the angular orientation of the field alone.

As this example illustrates, the observation of GIC when properly placed in context provides an ability to develop an important metric for calculation of the driving geo-electric field that caused the GIC.

Validating the NERC Geo-Electric Field for Ottawa and New England Ground Models

As the previous discussion has revealed, the knowledge of GIC flows combined with the network resistance characteristics and locations of network assets can provide all of the information needed to fully resolve the storm Geo-Electric Field Intensity at any particular time during the storm. In other words knowing I and R allows the application of Ohm's law and geometry to derive V or the Geo-Electric Field. This means that GIC measurements can be utilized to derive the geo-electric field at all observation locations and provide important validations of the NERC Ground Models and Geo-Electric Field calculation methodology.

To better understand how GIC can be used to validate the NERC geo-electric field calculations, the regional nature and footprint of each storm needs to be more fully explained. Figure 13 provides a map of the Ottawa and St John's geomagnetic observatories and their proximity to the Chester substation in Maine. As this map illustrates, Chester is positioned in between these two observatories with Ottawa being ~550 km west of Chester and St. Johns being ~1230 km to the east of Chester.

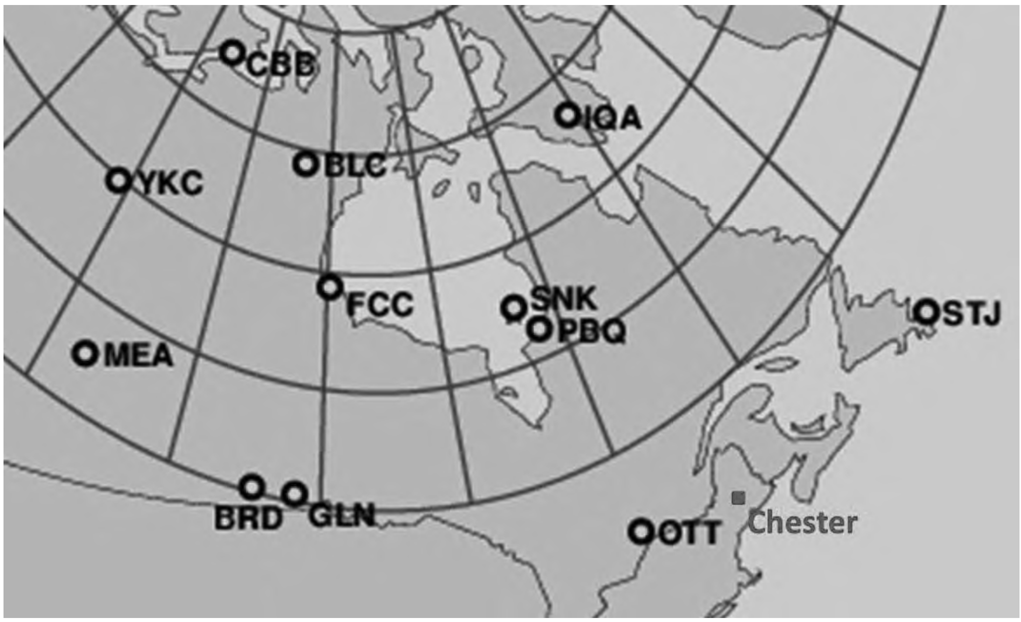


Figure 13 – Map showing Locations of Chester substation in comparison with Ottawa and St. Johns geomagnetic observatories

During the time period around 4:39UT which resulted in the peak GIC flow at Chester, both the Ottawa and St. John's geomagnetic observatory also recorded similar impulsive disturbance levels. This plot of these two observatories is shown in Figure 14. Because both of these observatories recorded this same coherent impulsive disturbance, this suggests that the observations had to be connected to the same coherent ionospheric electrojet current structure (in this case an intensification of the Westward Electojet Current) that would have extended all the way between these observatories and directly in proximity to Chester, Maine as well.

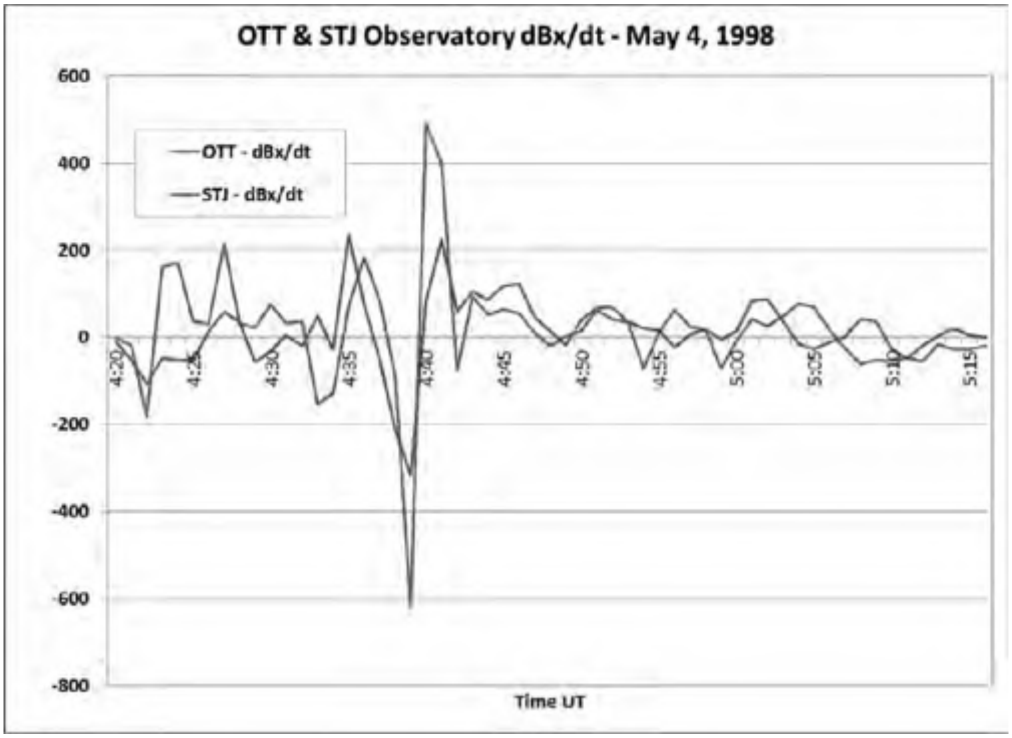


Figure 14 – Observed Impulsive disturbance at Ottawa and St. John's on May 4, 1998 at time 4:39UT.

At Chester some limited 10 second cadence magnetometer data was also observed during this storm, and Figure 15 provides a plot of the delta Bx at Ottawa (1 minute data) compared with the Chester delta Bx (10 sec) during the electrojet intensification at time 4:39UT. As this comparison illustrates that at this critical time in the storm, the disturbances at both Ottawa and Chester were nearly identical in intensity.

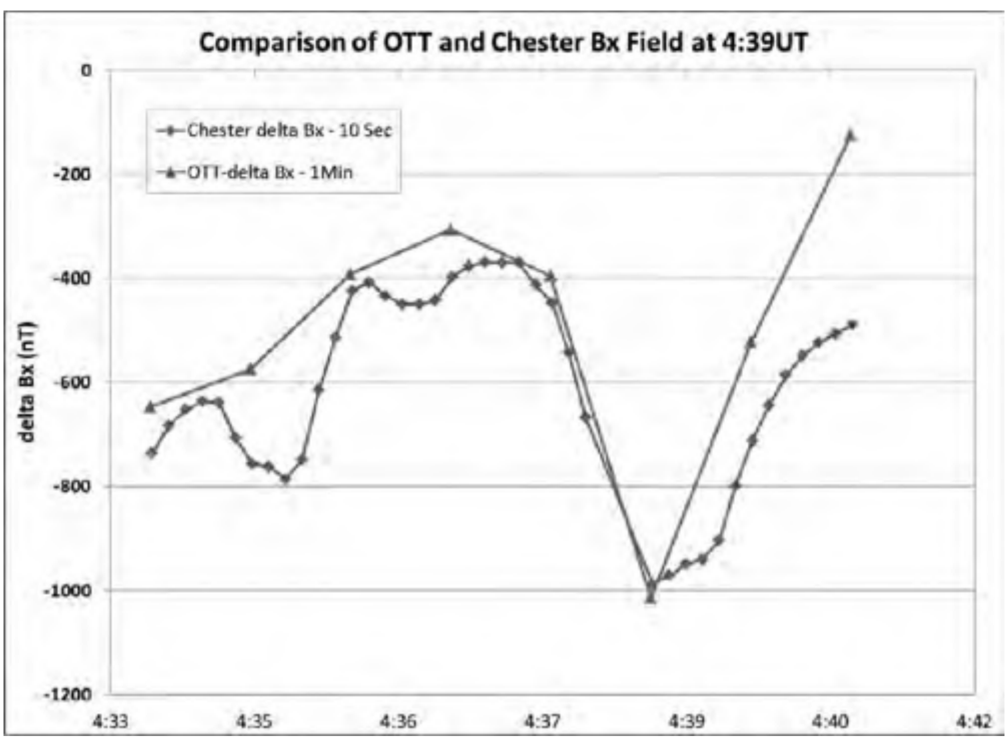


Figure 15 – Observation of Bx at Ottawa and Chester during peak impulse at time 4:39UT.

This close agreement between the observations at Ottawa and at Chester therefore allows the comparison of geo-electric field estimates between these two sites to be compared. As we had previously established using Ohm's Law, the peak geo-electric field must reach ~2 V/km to create the level of GIC observed during this storm. Geo-electric field calculations using a simulation model developed by the NERC GMD Task Force can be compared with the simulated geo-electric field in the Metatech simulation[4]. This comparison is shown in Figure 16. In addition, several portions of this geo- electric field waveform comparison are noted.

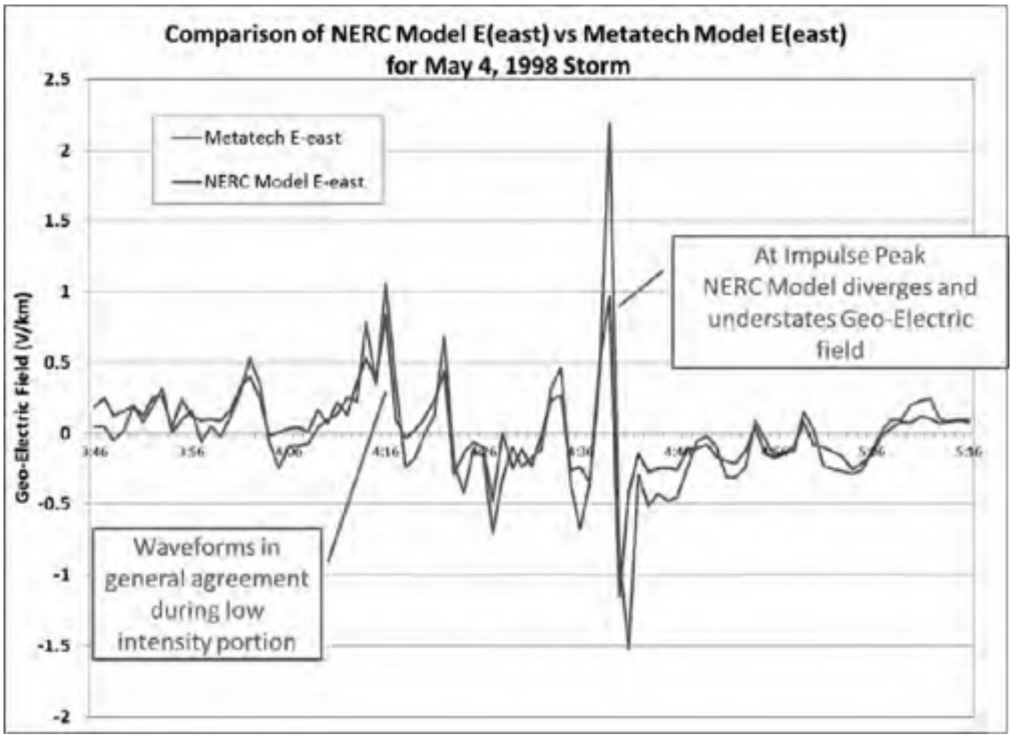


Figure 16 – Comparison of Metatech east-west geo-electric field calculation and NERC east-west geo-electric field calculation for May 4, 1998 storm event.

In the earlier portions of the storm simulation, the relative agreement between the two models for the geo-electric field is quite close. This occurs during a quieter and less intense portion of the storm. However as shown at the large impulse around time 4:39 UT, there is a divergence of agreement between the two models with the NERC modeling method understating the Metatech model results by a significant margin. After that impulse is over, the two models again come into relatively close agreement again. This suggests a problem in the NERC model of understating the intensity for more intense impulsive disturbances. As previously shown, the intensity in dB/dt is ~600 nT/min at time 4:39 UT, while it is generally below 100 to 200 nT/min at all other times during the simulation. Hence this higher intensity may be an important inflexion threshold within the NERC model.

As previously discussed Ohm's Law requires a sufficiently large enough geo-electric field to create the GIC flow observed at this location. Using the NERC model geo-electric fields it is possible to calculate the GIC flow and compare this to the GIC flow calculated for the Metatech model and even to the observed GIC. Figure 17 provides a comparison of the NERC model GIC with that computed in the

[4] Geo-elctric field data for this storm downloaded from NRCan http://www.spaceweather.gc.ca/data-donnee/dl/dl-eng.php#view

Metatech model. Figure 18 compares the same NERC Model GIC result with actual GIC observed at Chester. As both of these figures illustrate, the NERC model results will under predict the GIC at the peak storm intensities. In the case of the peak at time 4:39UT the understatement was similar in both the model comparisons and the observed GIC comparison.

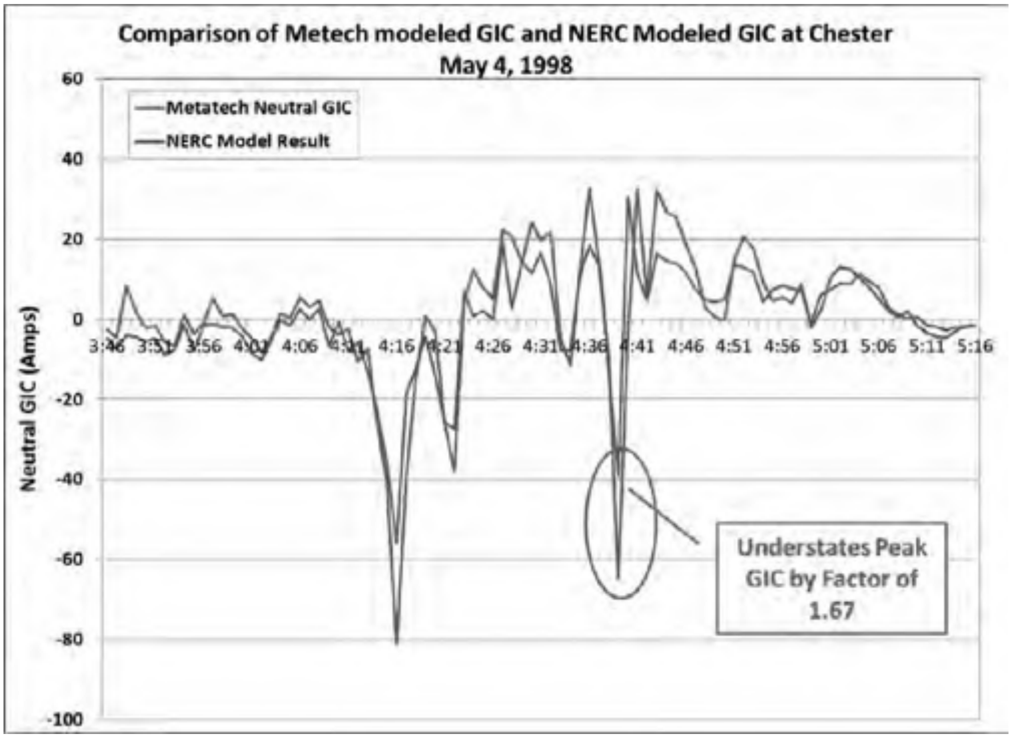


Figure 17 – Comparison of Metatech model GIC to NERC model GIC at Chester.

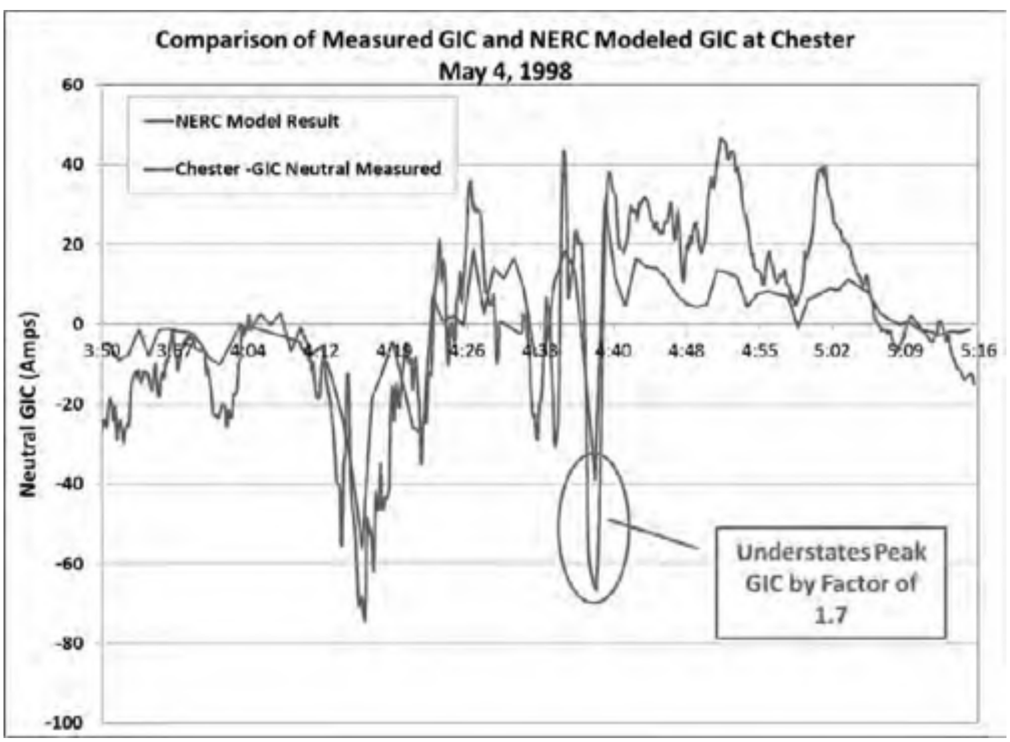


Figure 18 - Comparison of NERC model GIC to observed GIC at Chester.

NERC Model Validation Problems and Other GIC Observations

Seabrook GIC Observations July 13-16, 2012

While a number of GIC observations have been made over the last few decades in the US, very little of this information has been made publicly available. However where there is public information, it is possible to examine that data in a similar manner to the observations in Chester.Last year, observations observations as provided in Figure 19 were reported for GIC observations at the Seabrook Nuclear Plant[5]. These observations indicated peak GIC intensities during this storm that reached levels of 30 to 40 amps several times during the storm. The peak of 40 Amps occurred on July 16, 2012.

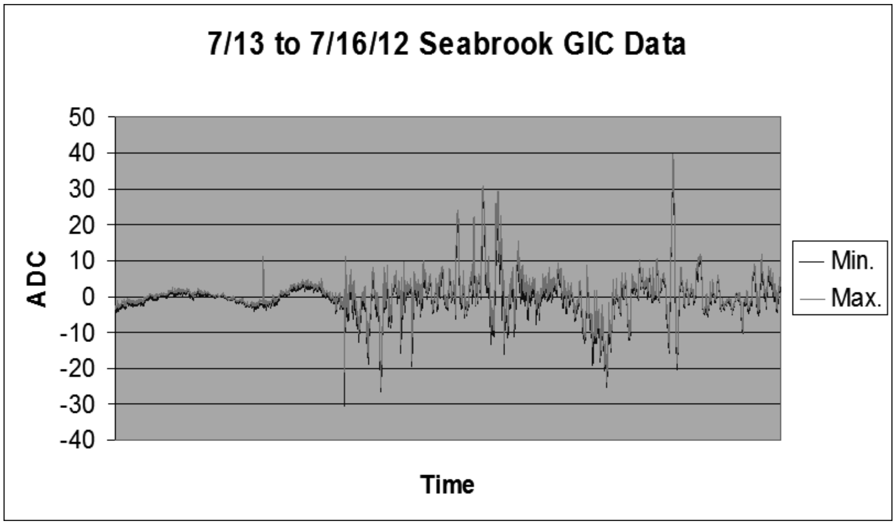


Figure 19 – GIC Observations at Seabrook Nuclear Plant July 13-16, 2012

Seabrook is also located in the New England region and because it is a GSU transformer, the neutral GIC also determines the flow that injects into the 345kV transmission network in that region. Figure 20 provides a map showing the location of Seabrook, and like Chester it will be heavily influenced by the same storm processes that will be observed at the nearby Ottawa observatory. In fact Seabrook is even closer to Ottawa than Chester.

[5] Geomagnetic Disturbance Mitigation for Nuclear Generator Main Power Transformers, Kenneth R. Fleischer, Presented April 16, 20132 at NOAA Space Weather Week Conference, Boulder Co.

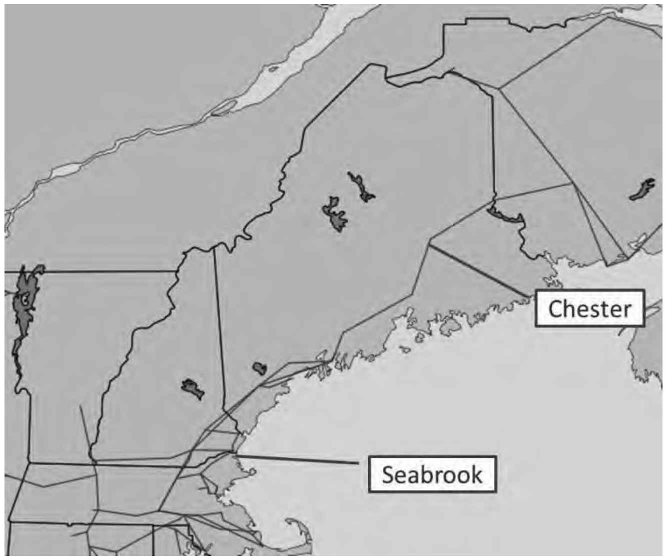


Figure 20 – Location of Seabrook Nuclear Plant in New England region 345kV network.

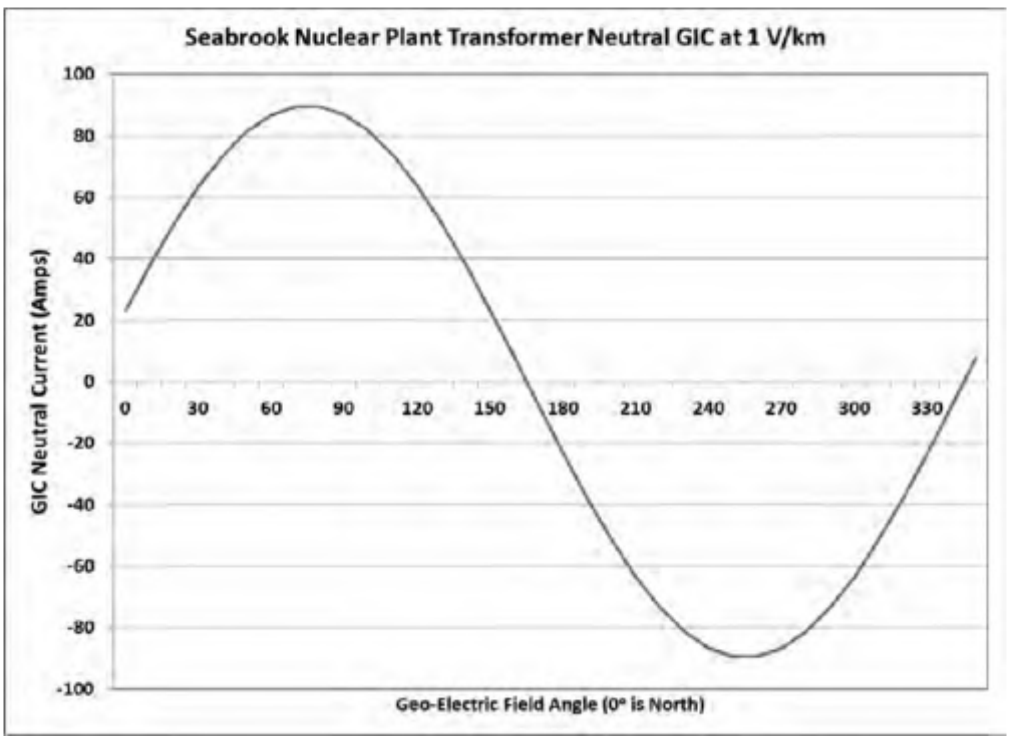


Figure 21 - GIC flow at Seabrook transformer neutral for 1 V/km geo-electric field at various orientation angles.

Figure 21 provides a plot of the characteristic GIC flows that would be observed at Seabrook for a uniform 1 V/km geo-electric field for a 360 degree rotation. This is computed similar to the way it was done at Chester. At this location, a 1 V/km geo-electric field produces ~90 Amp GIC at an 80^{o} angle (essentially nearly east-west oriented). Compared to the characteristic GIC plot for Chester (Figures 7 and 11), for a 1 V/km geo-electric field at Seabrook the GIC will be ~50% higher. This is due to the more integrated connections at Seabrook into the New England 345kV grid and lower circuit impedances, as would be expected. This characteristic indicates that for the 40 Amp GIC observation that occurred on July 16, 2012, there must have been a net east-west geo-electric field of ~0.45 V/km to produce this large of a GIC, a requirement dictated by the Ohm's law behavior of the circuit at Seabrook.

Figure 22 provides a plot of the East-West Geo-Electric Field that would be derived using the NERC model from this storm, using the Ottawa observatory geomagnetic field disturbance conditions as the input. As shown the peak field intensity reaches only ~0.1 V/km which is ~4 times too low to produce the actual GIC observed at Seabrook for this storm event. Hence this storm simulation model provides an example of even worse GIC validation attempt than at Chester. (Not shown is that the peak north- south geo-electric field would have been ~0.12 V/km. But these are also too low and would not couple efficiently with the Seabrook region circuits; therefore this was not a factor in the GIC levels at Seabrook.)

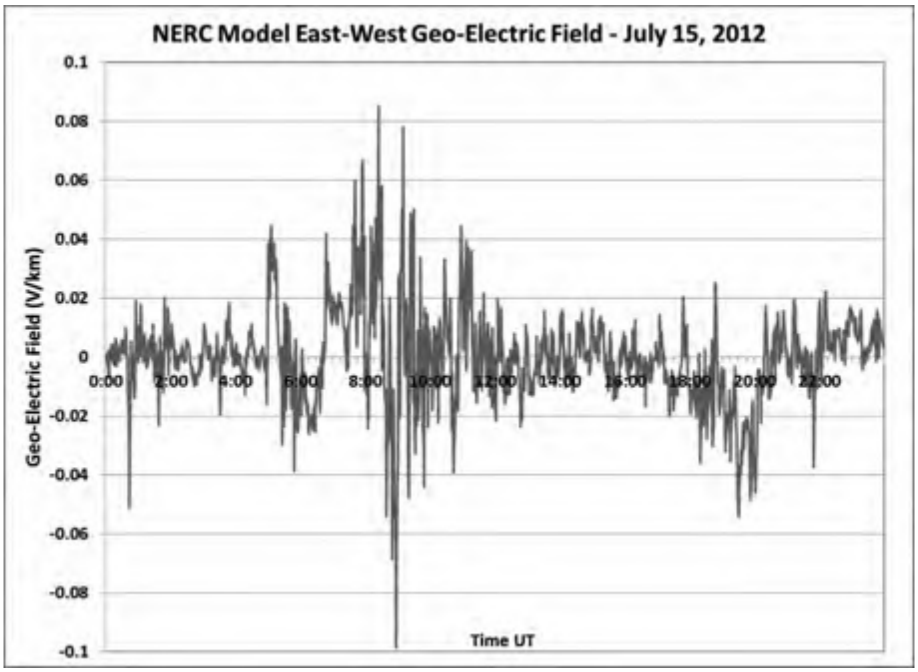


Figure 22 – NERC Model estimated East-West Geo-Electric Field on July 15, 2012 for the NE1 ground model.

BPA Tillamook GIC Observations Oct 30, 2003

In another situation, an examination has been conducted for ground models in the Pacific northwest region of the US. Data on GIC observations in the BPA transmission system have been provided to the Resilient Society Foundation under FOIA provisions and have been provided for analysis and ground model validation purposes. The GIC observations at the BPA Tillamook 230kV substation are examined in this case study. The Tillamook substation is on the western end of the BPA transmission network as shown in the map in Figure 23. There is a single 230kV line from Tillamook to the Carlton substation, but also 3 115kV lines that also connect at Tillamook, two which go in mostly North-South directions and one that connects to the East at Keeler.

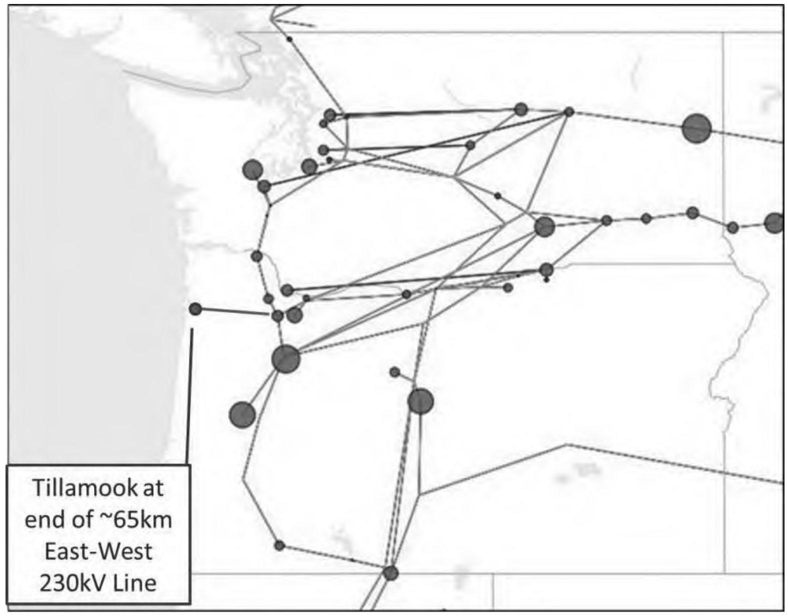


Figure 23 – Map of Tillamook 230kV substation and BPA 500kV network

Figure 24 provides a set of observations of GIC over a 2 hour time period at Tillamook which BPA provided in both 5 minute average and 2 second cadences during the October 30, 2003 storm. As shown in the 2 sec cadence data, the peak GIC approached nearly 50 Amps around time 19:55UT.

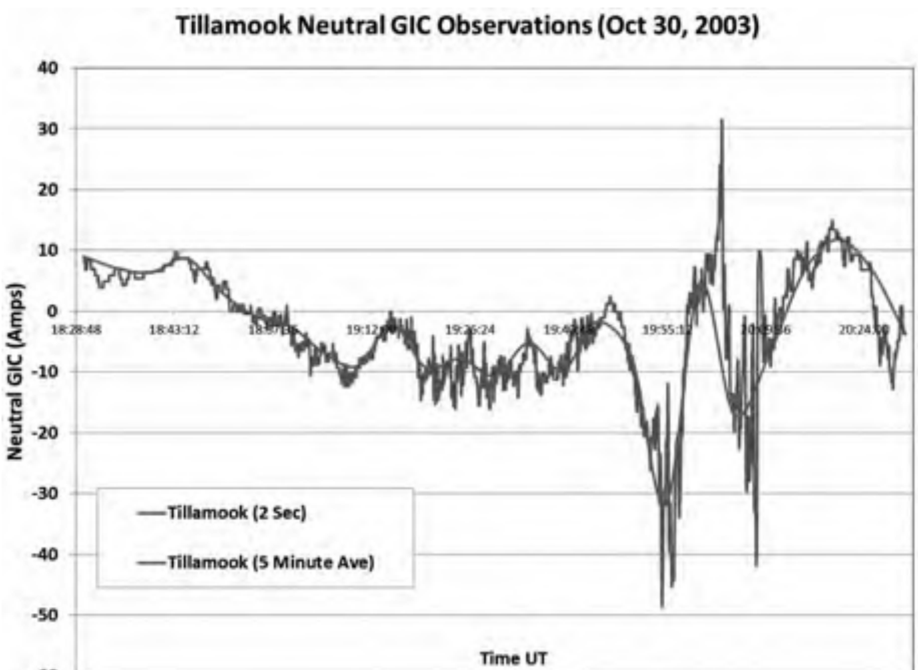


Figure 24 – Tillamook Neutral GIC observations on Oct 30, 2003, both 2 second and 5 minute average levels are shown

The Oct 30, 2003 storm conditions around time 19:55 UT are summarized from regional geomagnetic observatories as shown in Figure 25. This summary indicates that a region of intensification did encroach down into the Tillamook proximity at this time and would have been responsible for the peak GIC flows observed at this time, though Tillamook was not exposed to the worst case storm intensities.

Figure 25 – Regional storm conditions at time 19:55UT October 30, 2003 at time of peak Tillamook GIC flows

Using methods similar to those developed for the Chester station and the various BPA physical data sources available, the characteristic GIC flows for the Tillamook 230kV autotransformer can be calculated for a rotated 1 V/km geo-electric field. The results for this are shown in Figure 26 and the peak GIC reaches a level of ~38 Amps for a predominantly east-west oriented geo-electric field. Therefore when examining the GIC levels observed at Tillamook on Oct 30, 2003, Ohm's law would constrain that the minimum geo-electric field in this region would need to exceed 1 V/km (in at least the east-west direction) to produce the nearly 50 Amps GIC peaks.

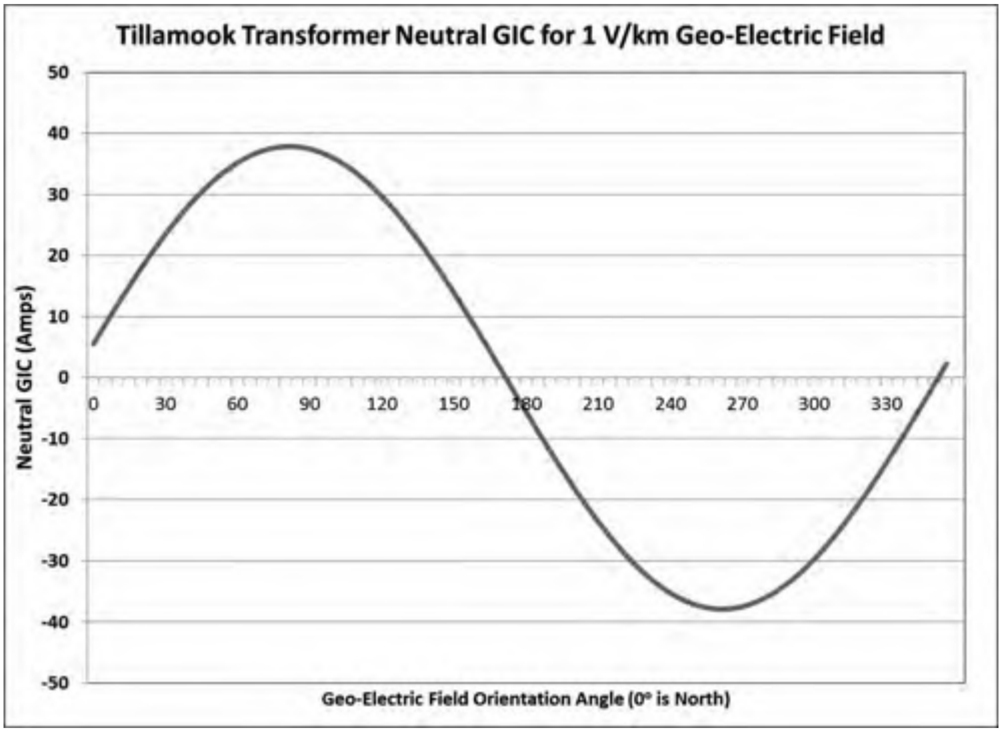


Figure 26 - GIC flow at Tillamook transformer neutral for 1 V/km geo-electric field at various orientation angles.

The NERC model calculations for East-West geo-electric field using the PB1 model are shown in Figure 27 for the same time interval as shown in Figure 24 for the Tillamook high GIC observations, but since the Tillamook GIC flow characteristics are defined in Figure 26, it is possible to utilize this to derive the minimum East-West geo-electric field responsible for producing the GIC flows in Figure 24. These results are also presented in Figure 27 with the NERC model predictions for this storm.

As Figure 27 shows, the peak geo-electric field as strictly constrained by Ohm's law must exceed 1 V/km during portions of the GIC flow where the Tillamook GIC exceeded ~38 amps level. At all times, the NERC model geo-electric field did not exceed even 0.25 V/km. As this comparison illustrates, the NERC model greatly understates the peak geo-electric field intensities at the peak GIC flow portions of the storm. In some cases this understatement is more than a factor of 4 to 5 times too small. This degree of divergence is also worse than what was observed at Chester Maine and is similar to the error level noted for Seabrook.

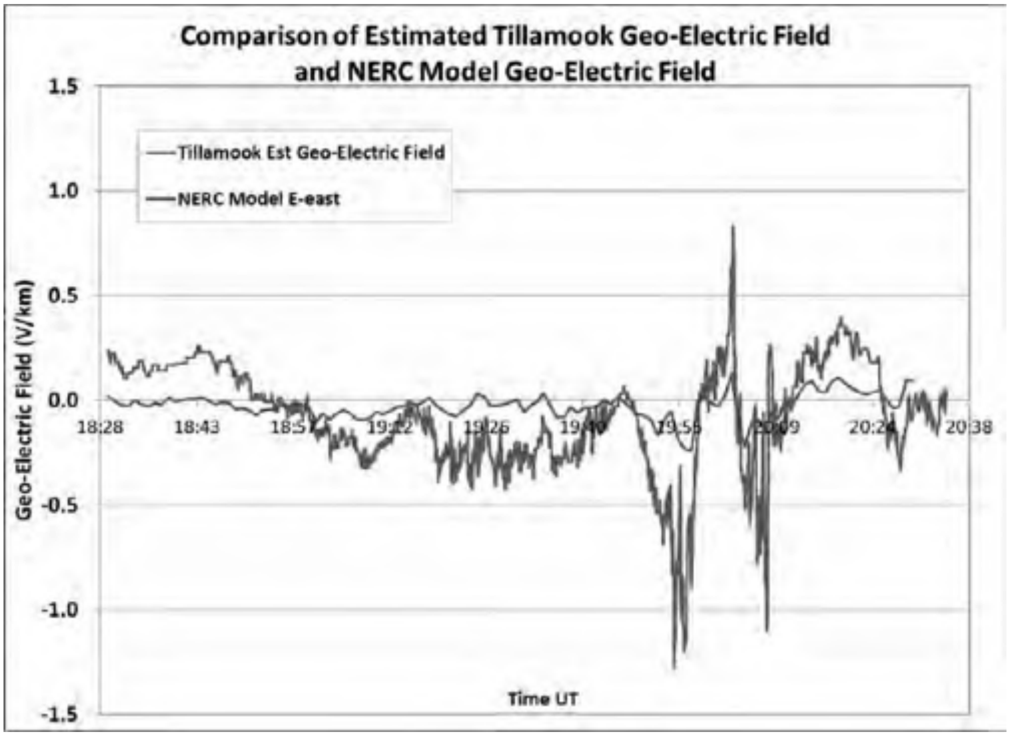


Figure 27 – Comparison of NERC Model geo-electric field with estimated geo-electric field needed to produce Tillamook GIC flows for the Oct 30, 2003 storm

There are other storms available with similar levels of GIC measurements observed at the Tillamook substation and 230kV line. Because this 230kV line is an East-West orientated line, GIC observed there will be largely driven by North-South variations (or dBx/dt) in the geo-magnetic field which subsequently produces an East-West geo-electric field. Figure 28 provides a plot of the nearest geomagnetic observatory (Victoria, ~340 km north of Tillamook) and the Tillamook GIC observed during an important storm on July 15-16, 2000. These geomagnetic disturbance conditions reach a peak of just over 150 nT/min resulting in GIC flows (5 min averaging) reaching -43.5 Amps at time 20:25UT. Figure 29 provides a detailed regional summary which show the more global storm conditions that were occurring at time 20:25UT over North America. As this Figure illustrates, the most severe storm conditions were located quite far to the North, so the GIC observed for these conditions could have been driven to much higher levels had the intensity extended further southward.

From the GIC observations for this storm, the minimal Geo-Electric field levels necessary to produce the GIC flows observed at Tillamook can be again calculated. This can also again be compared with the estimates used by NERC in modeling this storm event, this comparison is shown in Figure 30. In the comparison of the NERC model geo-electric field with the actual geo-electric field as derived from GIC measurements, the NERC model again greatly under predicts peak V/km intensities, by as much as a factor of ~5 or more at peak intensities times. These results are similar to the results from the Oct 30, 2003 storm as shown in Figure 27 and further confirm that the NERC models will not accurately depict storm conditions.

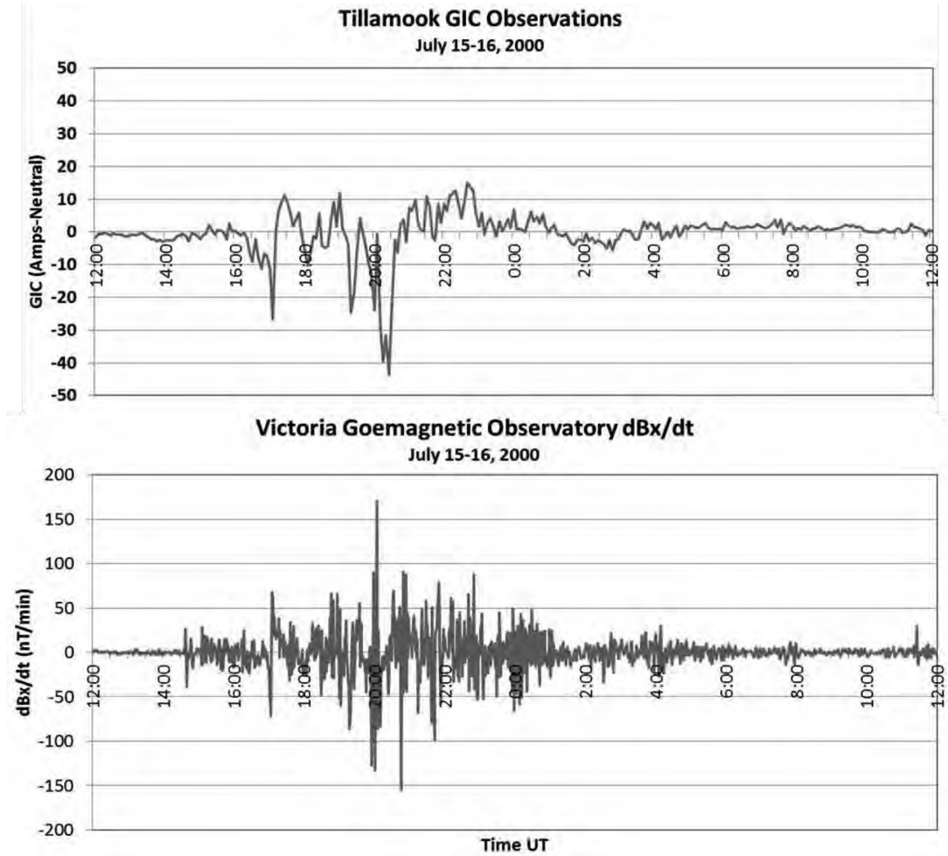


Figure 28 – Observed Tillamook GIC and Victoria dBx/dt for storm on July 15-16, 2000.

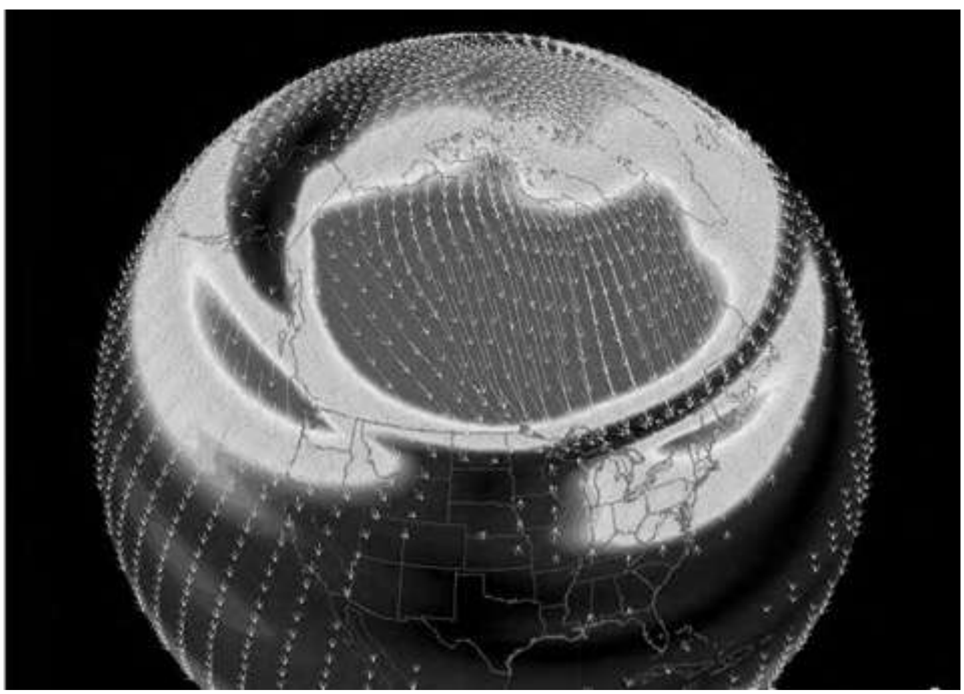


Figure 29 - July 15, 2000 at time 20:25UT storm conditions at time of Tillamook -43.5 Amp GIC Peak.

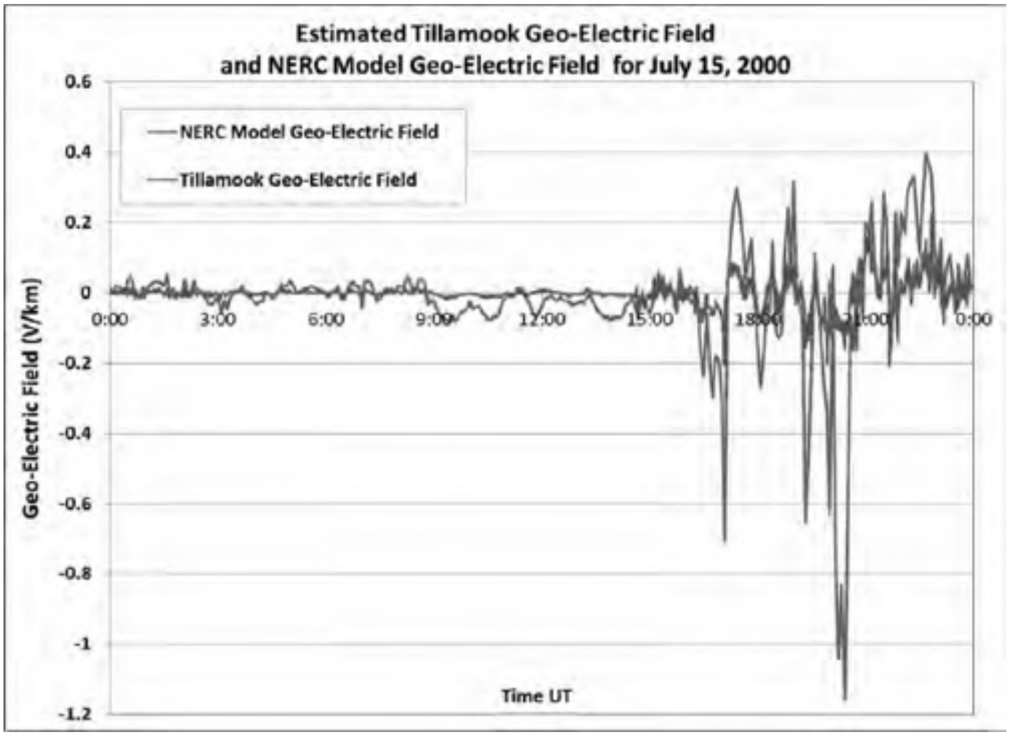


Figure 30 - Comparison of NERC Model geo-electric field with estimated geo-electric field needed to produce Tillamook GIC flows for the July 15, 2000 storm

Other Instances of Geo-Electric Field Modeling Concerns

The NERC geo-electric field simulation tools had their genesis out of the Finnish Meteorology Institute and have since been adopted at NASA (A. Pulkkinen) and also at Natural Resources Canada and many other locations around the world. Pulkkinen in particular was a key NERC GMD Task Force science investigator, a key EPRI science investigator along with staff from NRCan. Pulkkinen was also a member of the NERC GMD Standards Task Force, where the draft standards incorporating these tool sets are fully integrated into the science analysis and are recommended tools for system analysis. In the entirety of the NERC GMD task force investigations, no evidence has been made available by the NERC GMD Task Force of rigorous validations of the suite of ground models and derived relationships that have been published. USGS scientist involved in the effort asked for more power industry efforts to do model validations at several NERC GMD meetings, with no active participants and no subsequent publications supporting the ability to verify these models.

These FMI/NRCan-based geo-electric field modeling approaches use a Fourier transform method[6]. Fourier transforms are well-conditioned for periodic signals, not the very aperiodic events associated with abrupt, high intensity impulsive disturbances typical for severe geomagnetic storms. Therefore a Fourier approach needs to be carefully considered and tested rigorously to assure fidelity in output resolution for severe impulsive geomagnetic field disturbances. An additional geo-electric field modeling approach has been developed by Luis Marti based upon Recursive Convolution[7]. Unfortunately no independent validation for this model was noted in their IEEE paper on the model, rather it was only

[6] How to Calculate Electric Fields to Determine Geomagnetically-Induced Currents. EPRI, Palo Alto, CA: 2013. 3002002149.

[7] Calculation of Induced Electric Field During a Geomagnetic Storm Using Recursive Convolution, Luis Marti, A. Rezaei-Zare, and D. Boteler, IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 29, NO. 2, APRIL 2014

tuned to agree with the FMI/NRCan geo-electric field model output results. In addition, staff from the NOAA SWPC and USGS were also provided tool sets that were tuned to the NASA-CCMC/NRCan geo-electric field models so that the results that each examined would be the same. Hence no real independent assessments were ever apparently undertaken by all of these organizations. Therefore all of the various NERC GMD models appear to produce results that will consistently understate the true geo-electric field intensity.

In looking at recent publications by Pulkkinen, et. al., a paper titled "Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden"[8] was published in the Space Weather Journal in 2008. In this paper the authors presented results from several storm events that were similar in intensity to the May 4, 1998 storm that was discussed in a prior section of this report. Figure 31 is a set of plots from Figure 7 of their paper showing the disturbance intensity (dB/dt in nT/min) in the bottom plot and the measured and calculated GIC in the top plot. As illustrated in this Figure, the storm intensity is similar to that experienced in Maine during the May 4, 1998 storm at ~500 nT/min. In regards to the comparison of the Measured and Calculated GIC the simulation model greatly under predicts the actual measured GIC during the most intense portion of the storm around hour 23 UT by substantial margins (factor of 3 or more). This is the same symptomatic outcome observed in the NERC model results and provides another independent assessment with possible inherent problems with this modeling approach.

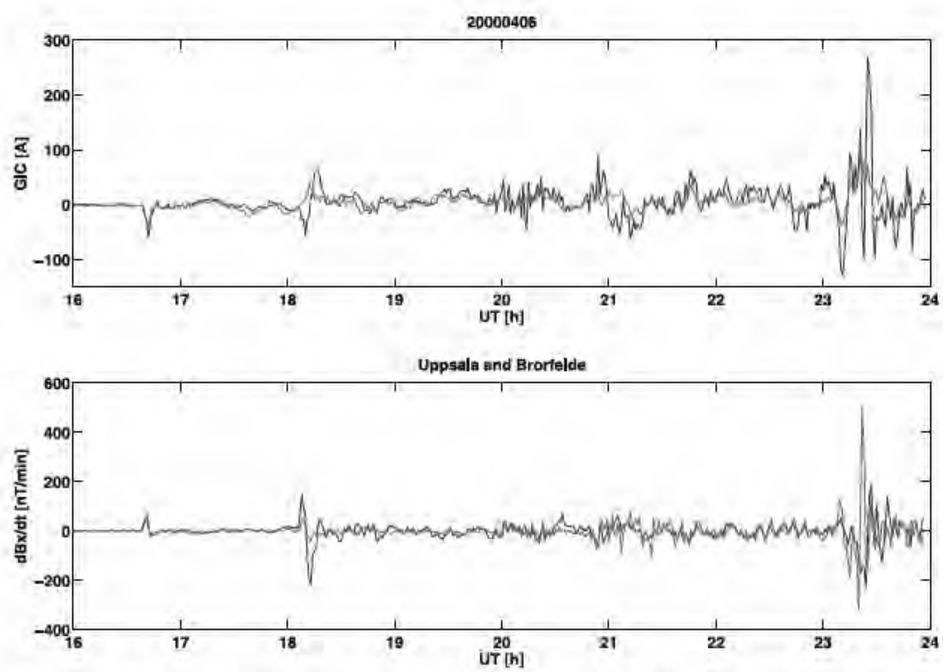


Figure 7. The top curve shows the measured (blue) and calculated (red) GIC at Simpevarp-2 (6 April 2000). The bottom curve shows dB_x/dt from Uppsala (blue) and Brorfelde (red).

Figure 31 – Plot Figure 7 from Pulkkinen, et.al.,paper "Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden" published 2008 showing storm intensity and GIC comparisons

[8] Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden, M. Wik, A. Viljanen, R. Pirjola, A. Pulkkinen, P. Wintoft, and H. Lundstedt, SPACE WEATHER, VOL. 6, S07005, doi:10.1029/2007SW000343, 2008

In another example from this same paper, a figure shown below as Figure 32 provides a comparison plot of the Measured and Calculated GIC during the July 15, 2000 storm at the same transformer in southern Sweden. The GIC results as in all prior comparisons greatly diverge during the occurrence of the largest and most sudden impulsive disturbance events, such as those between 21 and 22 UT.

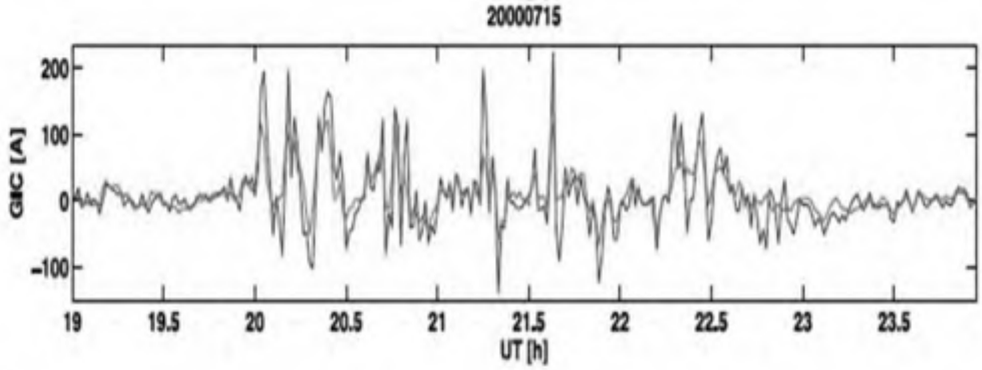


Figure 4. Measured (blue) and calculated (red) GIC at Simpevarp-2 for three events in 1998 to 2000.

Figure 32 - Plot Figure 4 from Pulkkinen, et.al.,Paper "Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden" published 2008 showing GIC comparisons

Conclusions – Draft NERC Standards are Not Accurate and Greatly Understate Risks

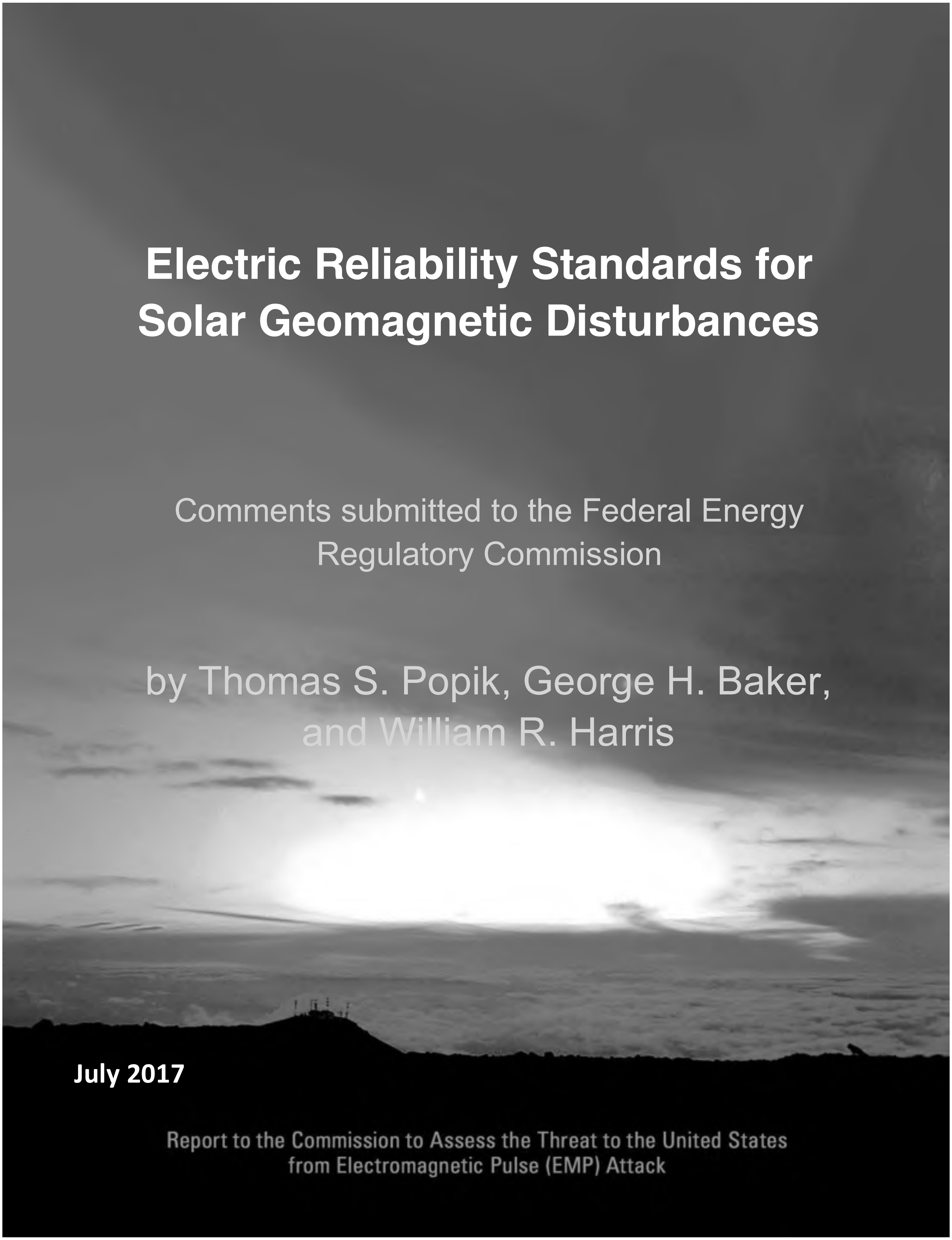
As these examples illustrate the results of calculations of geo-electric fields by the NERC models and any subsequent NERC predicted GIC's appear to exhibit the same problems of significantly under predicting for intense storm disturbances. In all locations that were examined the results of the models consistently under predicted what Ohm's Law establishes as the actual geo-electric field. This is a systemic problem that is likely related to inherent modeling deficiencies, and exists in all models in the NERC GMD Task Force and likely in many other locations around the world.

This has significant implications for nearly all of the findings of the NERC GMD Task Force. These erroneous modeling approaches were utilized to examine the peak geo-electric field outputs to much higher disturbance intensities for severe storms. For example the underlying analysis performed by NERC Standard Task Force members Pulkkinen and Bernabeu[9] for the 100 Year storm peaks utilized the faulty geo-electric field calculation model to derive the peak geo-electric fields for the reference Quebec ground models. This would drastically understate the peak intensity of the storm events by the same factor of 2 to 5 ratios as noted in the prior case study analysis. Therefore the standard proposing the NERC Reference Field level of between 3 to 8 V/km would be an enormous under-estimation and result in an enormous miss-calculation of risks to society. The same modelling errors are part of all earlier Pulkkinen/Pirjola[10] derived science assessments which also examined these peaks and 100 year storm statistics. As all prior validations within this report have established, the NERC geo-electric field model under predicts geo-electric field by a factor of 2 to 5 for the most important portions of storm events. Hence these errors have been entirely baked into the NERC GMD Task Force cake and their draft standards as well. Therefore the entirety of the Draft Standard does not provide accurate assessments

[9] Pulkkinen, A., E. Bernabeu, J. Eichner, C. Beggan and A. Thomson, Generation of 100-year geomagnetically induced current scenarios, Space Weather, Vol. 10, S04003, doi:10.1029/2011SW000750, 2012.

[10] Pulkkinen, A., R. Pirjola, and A. Viljanen, Statistics of extreme geomagnetically induced current events, Space Weather, 6, S07001, doi:10.1029/2008SW000388, 2008.

of the geo-electric field environments that will actually occur across the US. It has also been shown in this White Paper that undertaking a more rigorous development of validated geo-electric field standards can be done in a simple and efficient manner and that such data to drive these more rigorous findings already exists in many portions of the US. Efforts on the part of NERC's standard team and the industry to withhold this material information are counter-productive to the overarching requirements to assure public safety against severe geomagnetic storm events. Such fundamental and significant flaws in technical calculations and procedural actions should not be a part of any proposed standard and a redraft must be undertaken.



Electric Reliability Standards for Solar Geomagnetic Disturbances

Comments submitted to the Federal Energy Regulatory Commission

by Thomas S. Popik, George H. Baker, and William R. Harris

July 2017

Report to the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack

The cover photo depicts Fishbowl Starfish Prime at 0 to 15 seconds from Maui Station in July 1962, courtesy of Los Alamos National Laboratory.

This report is a product of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. The Commission was established by Congress in the FY2001 National Defense Authorization Act, Title XIV, and was continued per the FY2016 National Defense Authorization Act, Section 1089.

The Commission completed its information-gathering in June 2017. The report was cleared for open publication by the DoD Office of Prepublication and Security Review on June 4, 2018.

REPORT TO THE COMMISSION TO ASSESS THE THREAT TO THE UNITED STATES
FROM ELECTROMAGNETIC PULSE (EMP) ATTACK

Electric Reliability Standards for Solar Geomagnetic Disturbances

Comments submitted to the Federal Energy Regulatory Commission

by Thomas S. Popik, George H. Baker, and William R. Harris

July 2017

July 2017

Dr. William R. Graham
Chairman
Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack

Dear Dr. Graham:

As you have requested, the nonprofit Foundation for Resilient Societies, Inc. has approved the transmittal of that organization's documentary filing on a **Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events** as a Staff Report to the Congressionally-mandated EMP Commission.

This Staff Report was originally produced in July 2015 and then filed as corrected on August 10, 2015 in public Docket RM15-11-000 of the Federal Energy Regulatory Commission (FERC). The document provides a set of research findings and supporting evidence relating to the then-proposed NERC Standard TPL-007-1. This standard utilizes a benchmark model and a set of threat thresholds to assess the need for hardware protection of critical electric equipment within the U.S. bulk power system. Our docket filing expressed concerns that an overly-optimistic threat benchmark would result in no required hardware protection and therefore leave the U.S. electric grid vulnerable to solar storms. Had a higher and more uniform threat benchmark been established by NERC, Standard TPL-007-1 could have also provided a significant degree of protection against man-made EMP.

On September 22, 2016, FERC approved the proposed NERC Standard TPL-007-1 in FERC Order No. 830. Despite multiple requests for rehearing, FERC reaffirmed that standard in FERC Order No. 830-A on January 19, 2017.

Authors of the Staff Report to the EMP Commission dated August 10, 2015, comprising 91 pages, are Thomas S. Popik, Chairman of the Foundation for Resilient Societies, and two of the Senior Advisors to the later-reconstituted EMP Commission, Dr. George H. Baker and William R. Harris.

Respectful submitted by

Wm. R. Harris

William R. Harris
Senior Advisor

UNITED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

Reliability Standard for	)	
Transmission System Planned Performance	)	**Docket No. RM15-11-000**
for Geomagnetic Disturbance Events	)	

COMMENTS OF THE FOUNDATION FOR RESILIENT SOCIETIES

Submitted to FERC on July 27, 2015
Corrected Comments submitted on August 10, 2015

Introduction

Pursuant to the Federal Energy Regulatory Commission's ("FERC" or "Commission") Notice of Proposed Rulemaking ("GMD NOPR") issued on May 16, 2015,[1] the Foundation for Resilient Societies ("Resilient Societies") respectfully submits Comments on the Commission's proposal to approve the framework of Reliability Standard TPL-007-1 of the North American Electric Reliability Corporation (NERC) as "just and reasonable," to approve specific requirements of the standard, and to direct NERC to develop modifications to Reliability Standard TPL-007-1 and submit informational filings.

[1] *Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events*, Notice of Proposed Rulemaking (NOPR), 151 FERC ¶ 61,134 (May 14, 2015) ("GMD NOPR"), 80 FR 29990 (May 26, 2015).

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Figures

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Background

In FERC Order 779, FERC directed NERC to develop Second Stage Geomagnetic Disturbance (GMD) Reliability Standards:[1]

> The Second Stage GMD Reliability Standards must identify *benchmark GMD events* that specify what severity GMD events a responsible entity must *assess for potential impacts* on the Bulk-Power System. If the assessments identify potential impacts from benchmark GMD events, the Reliability Standards should require owners and operators to develop and implement a plan to protect against instability, uncontrolled separation, or cascading failures of the Bulk-Power System, caused by damage to critical or vulnerable Bulk-Power System equipment, or otherwise, as a result of a benchmark GMD event. (Emphasis added.)

As we will show in this comment, both the Benchmark GMD Event and the assessment criteria to identify potential impacts from the Benchmark GMD Event are fatally flawed. As a result, it is exceedingly unlikely that GMD Vulnerability Assessments by owners and operators will result in any significant protection against instability, uncontrolled separation, or cascading failures of the Bulk-Power System, except by voluntary action beyond the requirements of this standard.

Framework of Standard TPL-007-1

Overlapping Thresholds for Solar Storm Threat and Assumed Invulnerability of Transformers

The fundamental framework of Standard TPL-007-1 is defective because it overlaps a low solar storm threat or “Benchmark GMD Event,” expressed in volts per kilometer, with a very high assumed invulnerability of transformers (also known as “Geomagnetically Induced Current (GIC) withstand rating”) expressed in amps per phase. Only transformers having a lower withstand rating than the modeled GIC from the Benchmark GMD event would undergo “thermal assessment” to determine if hardware protection might be required.

If Standard TPL-007-1 were to use the same units of measure for both the assumed transformer invulnerability (GIC withstand rating) and the Benchmark GMD Event, it would be obvious that

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[1] *Reliability Standards for Geomagnetic Disturbances*, Docket No. RM12-22-000; FERC Order No. 779, 143 FERC ¶ 61,147 (May 16, 2013) (“FERC Order 779”), 78 FR 30747 (May 23, 2013), p. 2.

these limits have been imprudently set and are inconsistent with available real-world data. Unfortunately, the methodology implicit in the standard's framework is inherently difficult for the casual observer to understand, perhaps intentionally so. We can illustrate with an analogy to automobile crash testing.

For example, suppose the National Highway Traffic Safety Administration (NHTSA) asked automobile manufacturers to set a standard to determine if automobiles should have airbags installed as a protective measure against "high speed crashes." Further suppose that the NHTSA avoided a mandate to the industry by not specifying the miles per hour of a "high speed crash" but instead let the auto industry set this benchmark. Finally suppose that the NHTSA also let the auto industry determine a threshold limit for assumed resilience or invulnerability of cars and their occupants to crashes. For example, this threshold limit for assumed invulnerability to crashes might be 15 miles per hour.

As a first step, the automobile industry might propose a reasonable figure for a "high speed crash" by taking a survey of the radar gun readings on major highways to determine the upper speeds at which people actually drive. Using upper speeds, the resulting benchmark for a "high speed crash" might be quite substantial—for example, 75 miles per hour. If this were the "high speed crash benchmark," all cars would probably need airbags installed. As an alternative, if the auto industry were to average the speed of travel on all types of roads, the benchmark could be considerably lower—for example, 50 miles per hour.

In the analogous case of Standard TPL-007-1, if the Benchmark GMD Event were to be set at the maximum threat level that had been estimated by the respected space weather scientists previously engaged in the NERC standard-setting process (30-40 volts/kilometer), many transformers might need hardware protection. Instead, the NERC Standard Drafting Team, consisting all of industry representatives except for one scientist, downwardly averaged the Benchmark GMD Event to 8 volts/kilometer. And instead of using maximum readings of geomagnetic disturbances recorded in the United States, the NERC standard-setting team opted to use averaged data from Northern Europe over a limited time period lacking any major solar storms.

Returning to the automobile airbag analogy, as a second step the industry might set a threshold limit for assumed invulnerability of cars and their occupants to crashes. Suppose in the absence of test data, this limit was initially set at 15 miles per hour. However, with the apparent goal of avoiding cost and redesign hassle of airbag implementation, further suppose the auto industry decided to reference tests of three automobile designs for crash resilience. After examining tests on *only three automobile designs*—the first test at 17 miles per hour, the second test without crash test dummies in the car and at 200 miles per hour, and the third test at speeds and conditions unavailable in a published paper or otherwise—the industry then extrapolated the results to determine that *every automobile design* would protect human occupants at crashes up to *75 miles per hour*.

In the analogous case of Standard TPL-007-1, the assumed invulnerability of transformers to damage from GIC was set in initial drafts of the standard at *15 amps per phase*. When industry representatives in the ballot body refused to vote in favor of a standard with this low GIC withstand threshold, the industry found tests on *only three transformer designs* and then extrapolated the results to conclude that *all transformer designs* are invulnerable to GIC up to *75 amps per phase*. Notably, none of the transformer tests referenced actually injected currents of 75 amps into a transformer under fully operational electrical load conditions—this asserted invulnerability to solar storms was based on paper studies using mathematical models.

Returning to the automobile airbag analogy, if the benchmark for a high-speed crash were set at 50 miles per hour and the assumed invulnerability of cars and their occupants to crashes were set at 75 miles per hour, then no cars would require airbags, because the vulnerability threshold (75 mph) exceeds the stress threshold (50 mph). The imprudent result would be obvious to the public—by personal real world observation, most people would know that cars commonly travel over 50 miles per hour and that passengers often die in crashes at speeds well below 75 miles per hour.

However, in the analogous case of Standard TPL-007-1, because the units for the solar storm threat and associated Benchmark GMD Event (in volts per kilometer) have been expressed differently than the units of assumed transformer invulnerability to GIC (in amps per phase), the imprudent result is not obvious to most casual observers. In fact, to make the units equivalent for comparison, one must have access to proprietary data of electric utilities and sophisticated modeling software.[2] Likewise, members of the public do not commonly observe GIC readings nor do they see transformers overheat and catch fire during solar storms.

In this docket comment, we will show that for nearly all transformers in two major networks, the modeled threat to large power transformers is below the assumed level of invulnerability. Moreover, we will show that purportedly invulnerable transformers in a major network, PJM Interconnection, have already experienced failure during solar storms far smaller than the Benchmark GMD Event.

Modeling of GIC Impacts

As utilities model their networks in advance of the standard's effective date and selectively release the results, it is becoming clear that the assumed transformer invulnerability to solar storms under the standard's "withstand rating" of 75 amps is almost always greater than the modeled GIC under the Benchmark GMD Event. As a result, the number of transformers needing thermal assessment under Standard TPL-007-1 would be trivial. It is also becoming clear that when networks are modeled using a more prudent benchmark event of 20 V/km and a more justifiable threshold for thermal assessment—for example, the "30 Amps At-Risk Threshold" in the FERC-sponsored Metatech-R-319 report[3]—significant numbers of transformers would need thermal assessment and potential hardware protection.

Below we present modeling results for three major networks: PJM Interconnection (PJM), Central Maine Power, and American Transmission Company (ATC). PJM modeling under the

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[2] The electric utility industry is in possession of GIC readings that would likely show the modelled GIC for the Benchmark GMD Event at particular transformer locations are below readings that have been already observed during smaller solar storms. However, GIC data that could expose the NERC standard as technically unjustified has been withheld from the standard-setting process, withheld from independent scientific study, and withheld from public view. For example, the Electric Power Research Institute (EPRI) has GIC readings from locations in the U.S. and Canada dating back to 1991, but nearly all of this data has been held as confidential and not used in NERC standard-setting.

[3] "Metatech R-319, Geomagnetic Storms and their Impact on the US Power Grid," John Kappenman, Metatech Corporation, Oak Ridge National Laboratory, January 2010, available at http://web.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-319.pdf, last accessed on July 26, 2015,

NERC Benchmark GMD Event shows only two transformers in their network would need thermal assessment.[4] Central Maine Power modeling shows that only one transformer out of 15 in their network would need thermal assessment under the NERC Benchmark GMD Event, but that 8 transformers, or 53%, would need thermal assessment under a 20 V/km benchmark event. ATC modeling shows that 24 out of 62 transformers, or 39%, would need thermal assessment under a 20 V/km benchmark event with a 30 amp “at-risk” threshold.

PJM System

As an example, we show modeling of estimated GIC for transformers during the benchmark solar storm within the PJM system spanning from Illinois to New Jersey. The modeling results below, presented by NERC Standard Drafting Team Chair Frank Koza, show that only two transformers in the PJM system have modeled GIC above the assumed transformer invulnerability of 75 amps.[5] Restated, only two transformers out of approximately 560 extra high voltage transformers within the PJM system would need vulnerability assessment—all other transformers within PJM would be assumed to be immune from GIC during the Benchmark GMD Event.

[4] A third transformer is modeled at over 74 amps per phase, so effectively three of about 560 extra high voltage transformers in the PJM system need formal assessment under the proposed TPL-007-1 standard.

[5] “NERC GMD Reliability Standards,” Frank Koza, PJM, Chair of NERC GMD Standard Drafting Team, INL Space Weather Workshop, Idaho Falls, ID, April 8, 2015, accessible at https://secureweb.inl.gov/gmdworkshop/pres/F_Koza_NERCGMDReliabilityStandards.pdf, last accessed July 26, 2015. The Frank Koza presentation is separately filed in this Docket as Resilient Societies’ Reference Document No. 4.

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

PJM Preliminary Thermal Assessment Results

- Transformers with the highest GICs (divide by 3 phases; peak electric field in PJM is ~3V/km)

Transformer Description	Area	Avg Neutral Current, pu (3 phase)	Avg Neutral Amps (3 phase)
765/26 #2	AEP	1.147	86.557
765/26 #1	AEP	1.059	79.952
500/22 #1	PJM	0.645	74.491
765/345 #1	AEP	0.919	69.322
765/138 #2	AEP	0.883	66.610
765/500 #1	AEP	0.870	65.680
500/22 #1	DVP	0.565	65.260
345/25 #5	CE	0.388	64.975
500/25 #1	PJM	0.554	63.982
500/22 #1	PJM	0.554	63.982
500/230 #1	DVP	0.539	62.256
500/22 #1	PJM	0.539	62.219
345/138/34.5 # 1	CE	0.369	61.810
765/345/33 #1	CE	0.726	54.762
345/22 #8	DEO&K	0.320	53.517
500/230 #2	DVP	0.443	51.158
500/230 #1	DVP	0.442	51.062
765/345 #3	AEP	0.651	49.102
345/34.5 #1	AEP	0.283	47.431

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Figure 1: Page 19 from presentation titled "NERC GMD Reliability Standards, Frank Koza, PJM, Chair of NERC GMD Standard Drafting Team, INL Space Weather Workshop, Idaho Falls, ID, April 8, 2015."[6]

As might be expected, PJM's modeling result is out of line with other published studies such as the Metatech R-319 study conducted by Oak Ridge National Laboratory and sponsored by FERC. The Metatech study showed approximately 330 transformers at risk, out of approximately 560 transformers in total, within the states of Pennsylvania, New Jersey, Delaware, Maryland, Virginia, West Virginia, Kentucky, Ohio, and Indiana, and Illinois that roughly overlay the PJM network.[7]

[6] Area abbreviations are as follows: AEP is American Electric Power, DVP is Dominion, CE is ComEd, DEO&K is Duke Energy Ohio and Kentucky. Notably, PSEG, owner of the Salem 1 and 2 nuclear plants with failed transformers during GMD events, is not among PJM "Transformers with the highest GICs" and not above a mandatory transformer Screening Criterion.

[7] PJM transformer at-risk estimates developed from "30 Amp At-Risk Threshold" tables on pages 4-15 and 4-15 of "Geomagnetic Storms and Their Impacts on the U.S. Power Grid," Oak Ridge National Laboratory, available at http://web.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-319.pdf, last accessed on July 26, 2015, filed as a reference document on FERC Docket No. RM15-11-000.

Had the NERC Standard Drafting Team collected and analyzed GIC data for transformers within the PJM network, and transformers in other areas of the United States, these data would have shown that the Benchmark GMD Event and its associated scaling factors for latitude and ground models have been set to estimate GIC levels far below real world observations. In fact, the July 30, 2014 analysis of John Kappenman and William Radasky in the NERC standard-setting comment, "Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard," shows that real world GIC readings are two to five times higher than what the NERC ground model and latitude scaling factors in the Benchmark GMD Event would predict.[8]

Had the NERC Standard Drafting Team collected, analyzed, and disclosed failure data for all transformers within the PJM network, and for transformers in other areas of the United States, these data would have shown that multiple transformer failures have occurred during geomagnetic storms far smaller than the storm of the Benchmark GMD Event. According to NERC's own incident report, the Phase "A" and Phase "C" Generator Step Up (GSU) transformers at the Salem 1 nuclear plant in New Jersey failed during the 13 March 1989 solar storm.[9] The magnitude of the March 1989 storm was about one-quarter of the magnitude of the Benchmark GMD Event and one-fifth the magnitude of the 1-in-100 year event estimated in the Metatech R319 report. Yet these same transformers, modeled by PJM at less than 75 amps during the Benchmark GMD Event, are exempted from mandatory thermal assessment and any consideration of required hardware protection under the NERC-FERC proposed standard. By PJM modeling and NERC standard setting, the Salem 1 nuclear plant transformers have now become invulnerable to solar storms:

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[8] Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard," John Kappenman and William Radasky, Comment in NERC GMD Phase 2 Standard Setting, July 30, 2014.

[9] "March 13, 1989 Geomagnetic Disturbance," North American Electric Reliability Council, July 9, 1990, available at http://www.nerc.com/files/1989-Quebec-Disturbance.pdf, last accessed on July 26, 2015, p. 19.

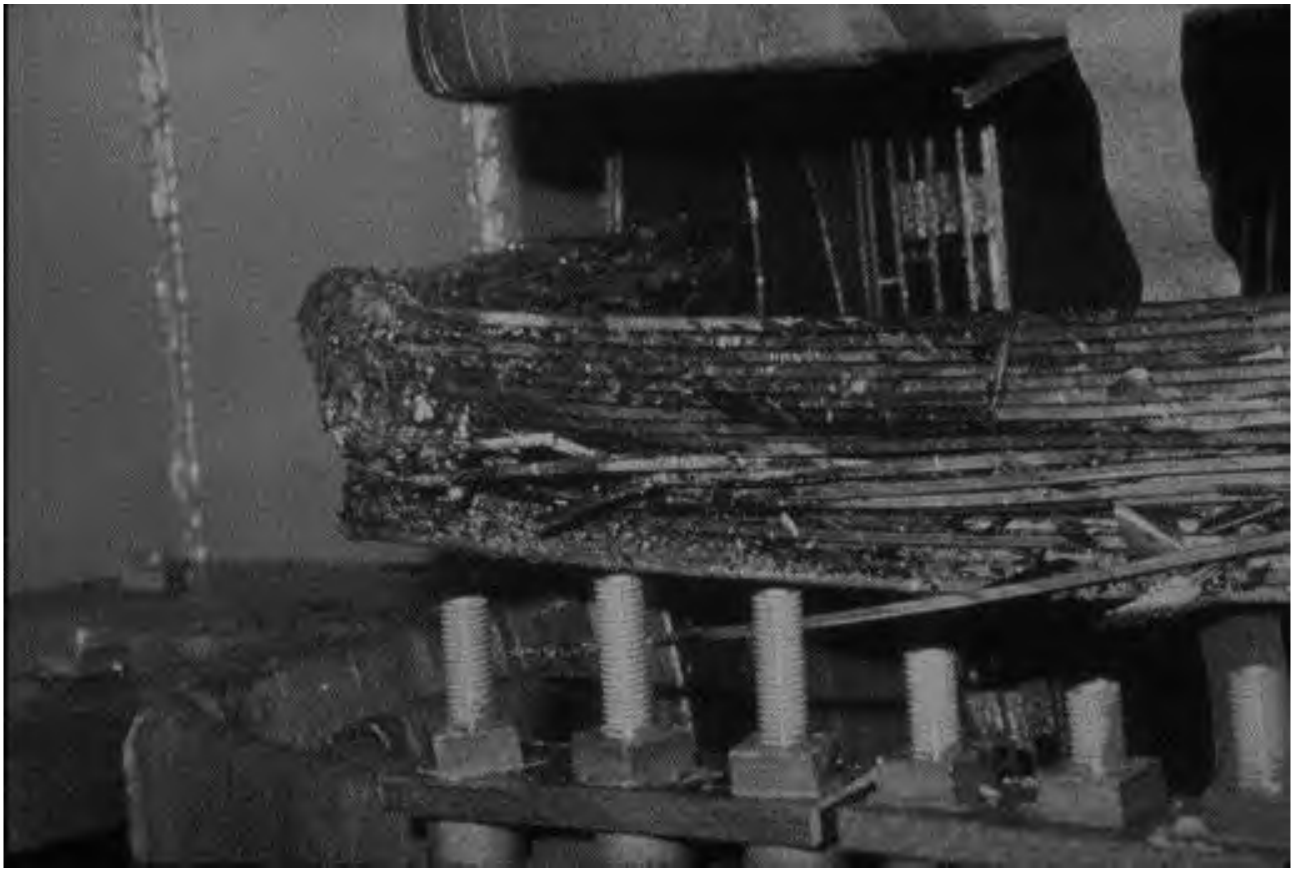

Figure 2: Melted Windings of Phase 1A Transformer at Salem Nuclear Plant in New Jersey in Aftermath of March 1989 Solar Storm
Source: Photo as displayed on page 2-29 of Metatech-R-319 Report

Central Maine Power

Because the NERC Standard Drafting Team set the Benchmark GMD Event at a fraction of observed data and because the assumed transformer invulnerability or “GIC withstand” is a high 75 amps, one would expect that only a few transformers might need protection under the requirements of the standard in other regions of the U.S. In fact, Central Maine Power (CMP) has modeled their system under the “NERC 1-in-100 year Benchmark” and found only one transformer in their whole network that would need assessment for solar storm vulnerability: the transformer at Chester, Maine.[10]

[10] "2014 Maine GMD/EMP Impacts Assessment, A Report Developed for the Maine Public Utilities Commission," Central Maine Power Co., December 2014, available as a reference document, p. 26.

Effective GIC A/phase for Maine transformers		Degree Amp Max	4.53 V/km NERC 1 in 100 year Benchmark	14 V/km Study team assumed 1 in 50 year event	20 V/km Study team assumed 1 in 100 year event	23.5 V/km Study team assumed 1 in 200 year event	29 V/km Study team assumed 1 in 500 year event
2 winding delta - wye	Chester SVC 18/345 kV	162	76	235	336	395	487
	Yarmouth GSU 22/345 kV #4	144	49	152	217	255	315
	Keene Road GSU 115/345 kV	160	32	98	140	165	204
2 winding Auto Xfmrs	Orrington 345/115 kV #1	64	4	14	20	23	29
	Orrington 345/115 kV #2	64	4	12	17	20	25
	South Gorham 345/115 kV #1	60	1	3	5	6	7
	South Gorham 345/115 kV #2	60	12	36	51	60	74
	Mason 345/115 kV #1	111	6	20	28	33	41
	Macguire Road 345/115 #1	30	27	83	120	139	172
	Keene Road 345/115 kV #1	160	6	18	26	31	38
3 winding Auto xfmrs	Coopers Mill 345/115 kV #3	30	35	109	155	182	225
	Surowiec 345/115 kV #1	38	17	52	75	88	108
	Albion Road 345/115 #1	30	60	186	266	313	386
	Larrabe Rd 345/115 #1	135	48	149	213	250	308

Table 1: Effective GIC in transformers for variations in geoelectric field[11]

For a 20 V/km geoelectric field event in Maine, the CMP modeling shows that 8 transformers, or 53%, would need thermal assessment and potential hardware protection with a 75 amp threshold for thermal assessment. CMP's modeling result is consistent in end result with the Metatech R-319 study sponsored by FERC—the Metatech study also showed that 8 transformers would be "at risk" in Maine, albeit under the "30 Amp At-Risk Threshold" scenario.[12]

Just as we see discordance between modeled GMD impacts within the PJM system and transformer failures in the real world, we see also discrepancies between modeled risk and real-world data in Maine. GMD modeling of the Chester transformer by John Kappenman and

[11] Ibid.

[12] FERC Commissioners should also take into account the total absence of NERC Benchmark GMD Event modeling of a "coastal effect" impacting transformers proximate to saline water bodies. Both the PJM and CMP transmission systems are subject to "coastal effects" that increase quasi-DC currents in coastal zone EHV transformers. See "Coastal Effect" Section of these comments, *infra.*

William Radasky, in their July 30, 2014 comment to NERC, estimates GIC of approximately 300 amps per phase during a severe solar storm of 5,000 nT/minute, four times the GIC that would be estimated using the NERC Benchmark GMD Event.[13]

The table below supplied by Central Maine Power shows real-world impacts within Maine over the past twenty-five years, including numerous equipment trips, which are inconsistent with the modeled result that only one transformer in Maine might need hardware protection. In fact, the disclosure by Central Maine Power shows GIC of up to 58 amps/phase during storms[14] that were a fraction of the GMD Benchmark Event.

[13] **"**Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard," John Kappenman and William Radasky, Comment in NERC GMD Phase 2 Standard Setting, July 30, 2014.

[14] CENTRAL MAINE POWER COMPANY; SMD ACTIVITY ARCHIVE; August 1991 to Present Dates" as presented to Maine State Legislature Joint Energy and Utilities Committee in March 2013, filed as a reference document on FERC Docket No. RM15-11-000. On June 21, 2001, the Central Maine Power SMD Activity Archive shows GIC of 173.4 amps in the neutral of the Chester, Maine transformer. To get amps per phase, this figure is divided by three for a result of 58 amps per phase.

CENTRAL MAINE POWER COMPANY
SMD ACTIVITY ARCHIVE
August 1991 to Present Date

(Chester SVC SUNBURST equipment in service since March of 91)

Storm Rating (Top 10)	Event Date	Chester SVC Transformer DC Neutral (A)	Storm Severity	Comments
1	**3/13/89**	**N/A**	**Severe**	**Hydro Quebec Blackout – All Orrington caps trip; Yarm 4 and MY gen vars went over +300 MVAR each; Orrington caps would not close back in**
	6/5/91	42.9	Major	Impacts to CMP unknown/not documented
	6/17/91	31.7	Major	Impacts to CMP unknown/not documented
	7/9/91	20.7	Moderate	Impacts to CMP unknown/not documented
	7/13/91	27.4	Moderate	Impacts to CMP unknown/not documented
	10/1/91	27.7	Moderate	Impacts to CMP unknown/not documented
	10/29/91	45	Major	Impacts to CMP unknown/not documented
	11/8/91	47	Major	Impacts to CMP unknown/not documented
	2/3/92	47.5	Major	Impacts to CMP unknown/not documented
	2/8-27/92	51.2	Major	Impacts to CMP unknown/not documented
	5/10/92	50	Major	Impacts to CMP unknown/not documented
	4/5/93	19.9	Moderate	Impacts to CMP unknown/not documented
	9/13/93	26.2	Moderate	Impacts to CMP unknown/not documented
	2/21/94	31	Major	Impacts to CMP unknown/not documented
	4/17/94	18	Moderate	Impacts to CMP unknown/not documented
	5/2/94	33.5	Major	Impacts to CMP unknown/not documented
	8/23/92	33.8	Major	Impacts to CMP unknown/not documented
	2/21/94	31	Major	Impacts to CMP unknown/not documented
	5/1/94	33.5	Major	Impacts to CMP unknown/not documented
	9/8/94	42	Major	Impacts to CMP unknown/not documented
4	**5/4/98**	**74.3**	**Severe**	**2 caps tripped at Orrington; Orrington Bus @ 328kV**
8	**10/22/99**	**61.3**	**Severe**	**NKI**
	1/28/00	-12	Minor	NKI
	2/12/00	-12	Minor	NKI
3	**4/6/00**	**81.7**	**Severe**	**SVC filter banks trip; distribution customers UPS's not functioning properly in North Coastal areas**
	5/24/00	52	Major	NKI
2	**7/15/00**	**-76**	**Severe**	**MS2 declared by ISO; Orrington KC3 trip; 7kV swing on 345kv system; many Auto xfmr LTC operations**
10	8/11/00	42.8	Major	**Surowiec KC2 trip - no apparent reason other than due to GIC**
9	9/17/00	-59.5	Major	NKI
	10/5/00	-28.4	Moderate	NKI
	12/00	N/A	N/A	Entire month of December saw constant minimal activity; nothing greater than 5A neutral peak and 4.1 6th harm peak but activity was present entire month

CENTRAL MAINE POWER COMPANY
SMD ACTIVITY ARCHIVE
August 1991 to Present Date

Chester SVC SUNBURST equipment in service since March of 91)

Storm Rating (Top 10)	Date	Chester SVC Transformer DC Neutral (A)	Storm Severity	Comments
6	**3/30/01**	**76.2**	**Severe**	**MIS G1 trip but think it was due to faulty control board – no other evidence for trip**
	4/11/01	-30.9	Major	NKI
	6/13/01	32.6	Major	May be an anomaly – one time spike with very little activity before or after spike
	6/21/01	173.4 ???	Severe	May be an anomaly – one time spike with very little activity before or after spike
	6/25/01	<5		Spike of 6th harm and very little neutral current flowing
	9/30/01	19.3	Moderate	NKI
	10/21/01	-21.5	Moderate	NKI
7	**11/5/01**	**63.6**	**Severe**	NKI
5	**11/24/01**	**89.9**	**Severe**	**Chester SVC filter banks trip**
	4/17-18/02	-15.0	Moderate	NKI
	4/19-20/02	21.1	Moderate	NKI
	9/4/02	17.0	Moderate	NKI
	5/29-30/03	60.6	**Severe**	NKI; 5/29/03; Kp of 8
	10/24 to 11/5/03	-98.0	**Severe**	NKI; 10/29/03 Very large GIC flow but no impacts seen by CMP
	7/24-27/04	52.5	Major	NKI; 7/27/04
	11/7-10/04	-88.0	**Severe**	NKI; 11/9/04
	1/17-22/05	52.2	Major	NKI; 1/21/05
	5/15/05	83.1	**Severe**	NKI
	8/24/05	96.9	**Severe**	Chester SVC Filter banks tripped
	9/11/05	33.4	Major	NKI
	12/14-15/06	37.5	Major	NKI; 12/14/06
	1/11-13/08	12.1	Minor	NKI; 1/11/08 Associated with Kp of 6
	1/17-19/08	39.9	Major	NKI; 1/18/08 Associated with Kp of 6
	3/25-28/08	8.6	Minor	NKI; 3/27/08 Associated with Kp of 6
	4/20 to 5/1/08	14.9	Minor	NKI; 4/20/08 Associated with Kp of 6
	3/31/09	10.5	Minor	
	6/24-25/09	7.1	Minor	NKI; 6/25/09 Associated with Kp of 6
	4/5-7/10	18.6	Moderate	NKI; 4/5/10 Associated with Kp of 6
	6/4/11	5.0	Minor	NKI
	6/5-8/11	9.6	Minor	NKI; 6/8/11 Associated with Kp of 6
	8/5-6/11	11.1	Minor	NKI; 8/5/11 Associated with Kp of 7
	9/9/11	3.7	Minor	NKI; Associated with Kp of 6
	9/26-27/11	24.7	Moderate	NKI; 9/26/11 Associated with Kp of 7
	10/24-25/11	22.1	Moderate	NKI; 10/24/12 Associated with Kp of 6

CENTRAL MAINE POWER COMPANY
SMD ACTIVITY ARCHIVE
August 1991 to Present Date
Chester SVC SUNBURST equipment in service since March of 91)

Storm Rating (Top 10)	Date	Chester SVC Transformer DC Neutral (A)	Event Severity	Comments
	1/24-25/12	7.3	Minor	NKI; 1/25/12 Associated with Kp of 6
	3/7-9/12	13.6	Minor	NKI; 3/9/12 Associated with Kp of 7
	3/12-15/12	5.7	Minor	NKI; 3/12/12 Associated with Kp of 6
	4/23-24/12	6.1	Minor	NKI; 4/23/12 Associated with Kp of 7
	6/16-18/12	20	Moderate	NKI; 6/16/12 Associated with Kp of 6
	7/13-16/12	5.4	Minor	NKI; 7/15/12 Associated with Kp of 6
	9/5/12	3.8		NKI; Associated with Kp of 6
	9/30 to 10/1/12	7.1	Minor	NKI; 10/1/12 Associated with Kp of 7
	10/8-11/12	12.6	Minor	NKI; 10/11/12 Associated with Kp of 6
	10/11/12	12.6	Minor	NKI; Associated with Kp of 6
	10/13/12	2.8		NKI; Associated with Kp of 6
	11/16/12	37.9	Major	NKI; Associated with Kp of 6
	11/14/12	6.3	Minor	NKI; Associated with Kp of 6

- Event Severity class based on Chester SVC SUNBURST 2000 GIC Recording standards/criteria
  - Storm ratings are based on magnitude of both the transformer neutral and 6th harmonic currents as well as the effect the storm had on CMP's system
- N/A – Chester SVC recording instrumentation not installed at this time or data not available
- NKI – No Known Impacts to grid

Table 2: Real-world GMD impacts in Maine over past twenty-five years.

American Transmission Company

American Transmission Company (ATC), a large electric utility that operates high-voltage electric transmission for much of Wisconsin, performed GIC modeling of their system using PowerWorld™ software. Modeling results for a variety of geoelectric field scenarios were presented in February 2013 at a GMD Task Force meeting held by NERC.[15]

Under a "30 amp At-Risk Threshold" and 20 V/km and below geoelectric field scenarios, a large proportion of ATC transformers would need thermal assessment.[16] In fact, 30% of ATC auto-transformers would need thermal assessment. Sixty-seven percent of ATC member Generator Step Up (GSU) transformers would need assessment. In total, of 62 ATC transformers, 24 (39%) would need thermal assessment. Notably, these ATC model results are largely consistent with the Metatech R-319 study sponsored by FERC. The Metatech study showed 27 transformers in Wisconsin would be at risk under a 30 amp threshold, approximately 59% of MVA capacity at the time of the study.

When a less stringent 75 amp threshold is applied to the ATC model results for geoelectric fields 20 V/km and below, the number of transformers needing thermal assessment is far lower—only 19% of ATC transformers would need assessment; 13% of autotransformers and 19% of GSU transformers. And under a 75 amp thermal assessment threshold and 2 V/km geoelectric field scenario (2 V/km geoelectric field would approximate the Benchmark GMD event scaled to Wisconsin), zero transformers in the ATC network would need thermal assessment.

[15] NERC GMD Task Force presentation "Geomagnetically Induced Current (GIC) What ATC is doing about it," excerpted from slide compendium "GMD Task Force Phase 2, Ken Donohoo, Task Force Chairman, In-Person Meeting, February 25-27, 2013, p. 16 of ATC presentation.

[16] The ATC GIC table is presented in "neutral amps" that combine currents from all three phases while the at-risk threshold for a single transformer would be "amps per phase." To make comparisons, the "30 amp At-Risk Threshold" scenario would need to be multiplied by a factor of 3 for a result of 90 amps in the neutral.

Hence, it should not shock FERC Commissioners that, with the NERC proposed hardware protection standard already submitted by NERC and under review by FERC, the owners of the generation facility within the ATC transmission system with the highest projected amps of GIC during a severe GMD event – NextEra Point Beach – opted not to purchase neutral ground blocking equipment or other protective equipment when installing a replacement 345 kV GSU transformer in the Spring of 2015.[17]

[17] The new Siemens GSU transformer at Point Beach was installed without GMD hardware protective equipment during the Spring 2015 maintenance outage. A senior engineer of Next Era Juno Beach was a member of NERC's GMD Task Force and would have known that the NERC-proposed standard would exempt Point Beach from mandatory hardware protections. See "Summary GIC Table for ATC GSU transformers," *infra*, showing the Point Beach GSU transformer as having the highest magnitude modeled GIC for East-West geoelectric fields postulated at either 2400 nT/sec (sic nT/minute) or 4800 nT/sec (sic nT/minute).

Summary GIC table for ATC auto-transformers						
	480 nt/sec storm		2400 nt/sec storm		4800 nt/sec storm	
	2V/km North	1V/km South	10V/km North	6V/km South	20V/km North	12V/km South
345 kV Auto-Transformers	N-S Field	E-W Field	N-S Field	E-W Field	N-S Field	E-W Field
Arcadian 345/138 #1	-0.7	-12.8	-3.3	-64.2	-6.5	-128.4
Arpin 345/138 #1	3.0	-4.2	15.0	-20.8	30.1	-41.6
Arrowhead 230/230 #1	30.9	-7.6	154.3	-38.1	308.7	-76.2
Arrowhead 345/230 #1	31.9	-25.5	159.6	-127.5	319.1	-255.1
Bain 345/138 #4	-2.2	3.1	-10.9	15.4	-21.9	30.7
Bain 345/138 #5	0.0	2.9	-0.1	14.3	-0.2	28.7
Columbia 345/138 #1	3.0	2.6	15.2	12.8	30.4	25.5
Columbia 345/138 #2	9.2	7.7	46.2	38.7	92.3	77.5
Columbia 345/138 #3	3.1	2.6	15.4	12.9	30.7	25.8
Dead River 345/138 #1	8.2	4.6	41.2	23.2	82.3	46.5
Dead River 345/138 #1A	9.8	5.5	48.9	27.6	97.9	55.3
Edgewater 345/138 #1	-0.2	23.3	-1.0	116.6	-2.0	233.3
Edgewater 345/138 #2	-0.2	21.8	-0.9	108.8	-1.8	217.5
Fitzgerald 345/138 #1	5.0	-23.5	-25.0	-117.7	-50.0	-235.4
Forest Junction 345/138 #2	12.8	1.4	64.2	7.1	128.3	14.1
Gardner Park 345/115 #1	-3.2	5.0	-16.2	25.1	-32.4	50.1
Gardner Park 345/115 #2	-3.2	5.0	-16.2	25.1	-32.5	50.3
Granville 345/138 #1	-18.5	1.8	-92.5	9.2	-184.9	18.4
Granville 345/138 #1	6.0	2.2	29.8	11.2	59.5	22.5
Kewaunee 345/138 #1	0.0	3.0	0.0	14.8	0.1	29.7
Kewaunee 345/138 #2	0.0	8.3	0.1	41.7	0.2	83.4
Morgan 345/138 #1	-10.5	12.4	-53.0	61.9	-105.9	123.8
N. Appleton 345/138 #2	5.1	-1.9	25.5	-9.3	51.0	-18.7
N. Appleton 345/138 #3	6.3	-5.8	31.7	-29.2	63.3	-58.4
N. Appleton 345/138 #1	9.4	-0.5	46.8	-2.7	93.6	-5.4
N. Madison 345/138 #1	-3.4	-5.1	-17.2	-25.4	-34.3	-50.8
N. Madison 345/138 #2	-3.4	-5.1	-17.2	-25.5	-34.5	-51.0
Oak Creek North 345/138 #1	-9.7	22.9	-48.6	114.7	-97.3	229.3
Oak Creek North 345/138 #2	-10.8	25.4	-53.8	126.9	-107.7	253.8
Oak Creek North 345/230 #2	-1.5	1.9	-7.4	9.7	-14.7	19.5
Oak Creek North 345/230 #1	-1.1	1.5	-5.7	7.4	-11.3	14.8
Paddock 345/138 #1	-4.6	-13.4	-22.9	-66.8	-45.8	-133.7
Plains 345/138 #1	14.5	-1.4	72.5	-6.9	145.0	-13.9
Racine 345/138 #1	-4.2	3.7	-21.2	18.7	-42.3	37.4
Racine 345/138 #2	-15.9	4.7	-79.5	23.7	-159.1	47.4
Rockdale 345/138 #1	1.7	2.3	8.4	11.3	16.7	22.6
Rockdale 345/138 #2	7.4	10.0	36.9	49.8	73.7	99.5
Rockdale 345/138 #3	5.1	6.8	25.3	34.2	50.6	68.4
Rocky Run 345/115 #1	-1.2	-0.8	-5.9	-4.2	-11.9	-8.4
Rocky Run 345/115 #2	-2.7	-1.9	-13.4	-9.6	-26.9	-19.1
Rocky Run 345/115 #3	-1.7	-1.2	-8.4	-6.0	-16.8	-11.9
Saukville 345/138 #1	17.0	29.6	85.0	148.2	170.0	296.4
South Fond Du Lac 345/138 #1	0.2	0.8	1.2	3.8	2.3	7.6
South Fond Du Lac 345/138 #2	0.2	0.7	1.1	3.7	2.3	7.4
Stone Lake 345/161 #1	-50.7	-22.8	-253.4	-114.0	-506.9	-228.1
W. Middleton/Cardinal 345/138 #1	7.9	-36.2	39.6	-181.0	79.3	-361.9
Werner West 345/138 #1	-28.1	-26.8	-140.7	-134.0	-281.5	-267.9

Summary GIC table for ATC member GSUs						
	480 nt/sec storm		2400 nt/sec storm		4800 nt/sec storm	
	2V/km North	1V/km South	10V/km North	6V/km South	20V/km North	12V/km South
345 kv GSU's	N-S Field	E-W Field	N-S Field	E-W Field	N-S Field	E-W Field
Columbia (WPL) 345/22 #1	49.1	-30.4	245.3	-152.0	490.6	-304.0
Columbia (WPL) 345/22 #1	49.5	-30.7	247.7	-153.5	495.4	-306.9
Cypress 345/35 #1	-19.9	-7.1	-99.5	-35.5	-198.9	-71.0
Edgewater (WPL) 345/22 #1	11.3	18.3	56.4	91.5	112.8	183.1
Edgewater (WPL) 345/22 #1	19.4	31.5	97.1	157.6	194.2	315.3
Gardner Park 345/19 #1	10.2	-20.7	50.9	-103.3	101.9	-206.7
Kewaunee 345/20 #1	19.0	30.8	95.1	154.0	190.2	308.0
Oak Creek North 345/25 #1	6.1	9.8	30.4	48.9	60.8	97.8
Oak Creek North 345/25 #1	6.3	10.2	31.6	50.9	63.2	101.8
Pleasant Prairie 345/24 #1	-12.2	4.2	-60.9	21.1	-121.8	42.2
Pleasant Prairie 345/24 #1	-12.1	4.2	-60.7	21.0	-121.3	42.0
Point Beach 345/19 #1	12.8	36.2	64.1	181.1	128.2	362.2
Point Beach 345/19 #1	14.5	36.4	72.7	182.2	145.4	364.3
SEC 345/18 #1	-19.0	0.3	-94.8	1.7	-189.5	3.3
SEC 345/18 #1	-18.8	0.3	-94.0	1.7	-188.0	3.3

Table 3: GIC values for Auto-Transformers and Generator Step-Up Transformers in the American Transmission Company network

Electric Grid Impacts during GMD Events

Resilient Societies compiled a list of significant electric grid impacts during GMD events. The impacts include transmission substations, HVDC links, and nuclear power plants. All impacts occurred during storms that were a fraction of the magnitude of the Benchmark GMD Event. The impact at the Seabrook nuclear plant in November 1998 was a vibration related event. The impacts were concentrated in areas where the coastal effect enhancement of GMD fields is operative and at higher latitudes. Nonetheless, two impacts occurred at lower geomagnetic latitude—the Contra Costa, California substation transformer failure and tripping of the Blackwater HVDC link.

As part of the standard-setting process, NERC should have requested data on electric grid impacts during solar storms from electric utilities. Had this been done, it would have likely shown that requirements and measures of the standard will not protect against GMD events lower than the Benchmark GMD Event. We ask the Commission to remand the standard for collection of relevant data on grid impacts during GMD events and incorporation of these data into the standard-setting process.

Significant Electric Grid Impacts During Geomagnetic Disturbance Events

Storm Date	Electric Grid Facility	City	State	Impact	Source
03/13/89	Contra Costa Substation	Los Medanos	CA	Transformer failure	IEEE Survey
03/13/89	Maine Yankee Nuclear Plant	Wiscasset	ME	Transformer damage	Resilient Societies
03/13/89	Salem 1 Nuclear Plant	Lower Alloways Creek	NJ	Transformer failure	NERC 3/89 GMD Report
09/19/89	Salem 2 Nuclear Plant	Lower Alloways Creek	NJ	Transformer failure	NERC 3/89 GMD Report
03/24/91	Radisson-Sandy Pond HVDC	Radisson	Quebec	HVDC Trip	L. Bolduc article, 2002
04/29/91	Maine Yankee Nuclear Plant	Wiscasset	ME	Transformer fire	Resilient Societies
05/28/91	Radisson-Sandy Pond HVDC	Radisson	Quebec	HVDC Trip	Boteler, et.al article, 1998
10/27/91	Radisson-Sandy Pond HVDC	Radisson	Quebec	HVDC Trip	ORNL/Sub/90-SQS8
10/28/91	Blackwater HVDC Tie	Clovis	NM	HVDC Trip	ORNL/Sub/90-SQS8
10/28/91	Radisson-Sandy Pond HVDC	Radisson	Quebec	HVDC Trip	Boteler, et.al article, 1998
11/10/98	Seabrook Nuclear Plant	Seabrook	NH	Transformer damage	Pacific NW Lab Report
04/06/00	Chester SVC	Chester	ME	UPS Malfunctions	Central Maine Power
07/15/00	Hope Creek Nuclear Plant	Artificial Island	NJ	Downrating to 55%	NRC Power Reactor Status
11/24/01	Chester SVC	Chester	ME	SVC Trip	Central Maine Power
07/15/12	Seabrook Nuclear Plant	Seabrook	NH	Downrating to 68%	Reuters News Service

Table 4: Select Impacts of GMD on Electric Grid Facilities

Figure 3: Select Locations of GMD Impacts on Electric Grid Facilities

Defects in Standard TPL-007-1

Technically Unjustified GMD Benchmark Event

In FERC Order 779, (p. 47):

> "71. In drafting the Commission ordered that benchmark GMD events be technically justified because responsible entities should not be required to assess GMD events (or protect against GMD events) "more severe" than the benchmark GMD (i.e., the rate of change in the GMDs magnetic fields), duration, geographic footprint of the GMD, how the GMD's intensity varies with latitude, system configuration, and the orientation of the magnetic fields produced by the GMD."

In FERC Order 779, (p. 2):

> "The Second Stage GMD Reliability Standards must identify "benchmark GMD events" that specify what severity GMD events a responsible entity must assess for potential impacts on the Bulk-Power System. The benchmark GMD events must be technically justified because the benchmark GMD events will define the scope of the Second Stage GMD Reliability Standards (i.e., responsible entities should not be required to assess GMD events more severe than the benchmark GMD events)."

The tolerant wording of this Commission order provided an incentive for NERC and members of the Standard Drafting Team to set a standard with a Benchmark GMD Event low enough for vulnerable transformers to escape mandatory hardware protection. As a regulatory body, it should be the duty of the Commissioners to recognize this end-run around the intent of the Commission and to instead ensure a technically justified Benchmark GMD Event.

Fortunately, the wording of FERC Order 779 (p. 47) provides good detail on the factors to be considered in setting the Benchmark GMD Event, including but not limited to varying severity of the GMD (i.e., the rate of change in the GMDs magnetic fields), duration, geographic footprint of the GMD, how the GMD's intensity varies with latitude, system configuration, and the orientation of the magnetic fields produced by the GMD:

> 102. We recognize that there is currently no consensus on benchmark GMD events, and the Commission does not identify specific benchmark GMD events for NERC to adopt. Instead, this issue should be considered in the NERC standards development process so that any benchmark GMD events proposed by NERC have a strong technical basis.

In our specific comments below, we show how NERC and the Standard Drafting Team have been systematically imprudent in consideration of nearly every important factor, resulting in a Benchmark GMD Event without a "strong technical basis."

Severity of GMD in 1-in-100 Year Reference Storm

In the GMD NOPR (p. 21), the Commission appropriately recognized that geoelectric field values used in assessments should reflect the real-world impact of a GMD event:

> 35. The geoelectric field values used to conduct GMD Vulnerability Assessments and thermal impact assessments should reflect the real-world impact of a GMD event on the Bulk-Power System and its components.

However, in standard setting, NERC and the Standard Drafting Team assiduously avoided collecting and/or analyzing real world data from within the United States and Canada, including magnetometer readings from United States Geological Service (USGS)[18] and Natural Resources Canada observatories;[19] measured and estimated geoelectric field data in published sources;[20]

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[18] Natural Resources Canada has geomagnetic and geoelectric field data available for display and download at http://www.geomag.nrcan.gc.ca/plot-tracee/geo-i-en.php.

[19] USGS has geomagnetic data available for display and download at http://geomag.usgs.gov/products/.

[20] For an example of published work on GMD data and impacts back to 1847, see "The Effects of Geomagnetic Disturbances on Electrical Systems at the Earth's Surface - An Update," Boteler, David, et.al, 37th COSPAR Scientific Assembly. Held 13-20 July 2008, in Montréal, Canada. (2008) p.353.

and measured GIC data from EPRI,[21] government-owned utilities (such as Tennessee Valley Authority (TVA) and Bonneville Power Administration (BPA),[22] and private utilities (such as PSEG, the owner of the Salem 1, Salem 2, and Hope Creek nuclear plants).[23]

The Standard Drafting Team also avoided using real-world GMD impact data from a variety of sources, including published reports, the Licensee Event Report (LER) database available from the U.S. Nuclear Regulatory Commission, and the Generating Availability Data System (GADS) and Transmission Availability Data System (TADS) databases held by NERC itself. NERC contracted with Storm Analysis Consultants, Inc. for production of the report "An Analysis of the Equipment Vulnerability from Severe Solar Storms, Storm-R-112," (August 25, 2011) but this report has apparently been withheld from public disclosure by confidentiality agreement. Had NERC and the Standard Drafting Team collected and analyzed available real-world data, they would have likely found that the severity of GMD in 1-in-100 Year reference storm had been set far below a technically justified level and without "strong technical basis."

The Commission was right to propose in the GMD NOPR (p. 23):

> 38. Next, the record submitted by NERC and other available information manifests a need for more data and certainty in the knowledge and understanding of GMD events and their potential effect on the Bulk-Power System. For example, NERC's proposal is based on data from magnetometers in northern Europe, from a relatively narrow timeframe with relatively low solar activity, and with little or no data on concurrent GIC flows. Similarly, the adjustments for latitude and ground conductivity are based on the limited information currently available, but additional data-gathering is needed. To address this limitation on relevant information, we propose to direct that NERC conduct or oversee additional analysis on these issues.

When a NERC committee of respected space weather scientists estimated a reference storm in February 2013,[24] the "preliminary results" were determined to be a maximum geoelectric field

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[21] EPRI has operated its SUNBURST network of GIC monitors since 1991; see "Sunburst Network for Geomagnetic Currents" available at http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001023278.

[22] Resilient Societies has obtained GIC data from both TVA and BPA using the Freedom of Information Act. BPA currently publishes real-time GIC data on its website at http://transmission.bpa.gov/business/operations/gic/gic.aspx.

[23] Resilient Societies requested GIC data from PSEG in 2011 and this request was declined.

of 30-40 V/km, as this slide from a contemporaneous presentation to the GMD Task Force presentation shows:[25]

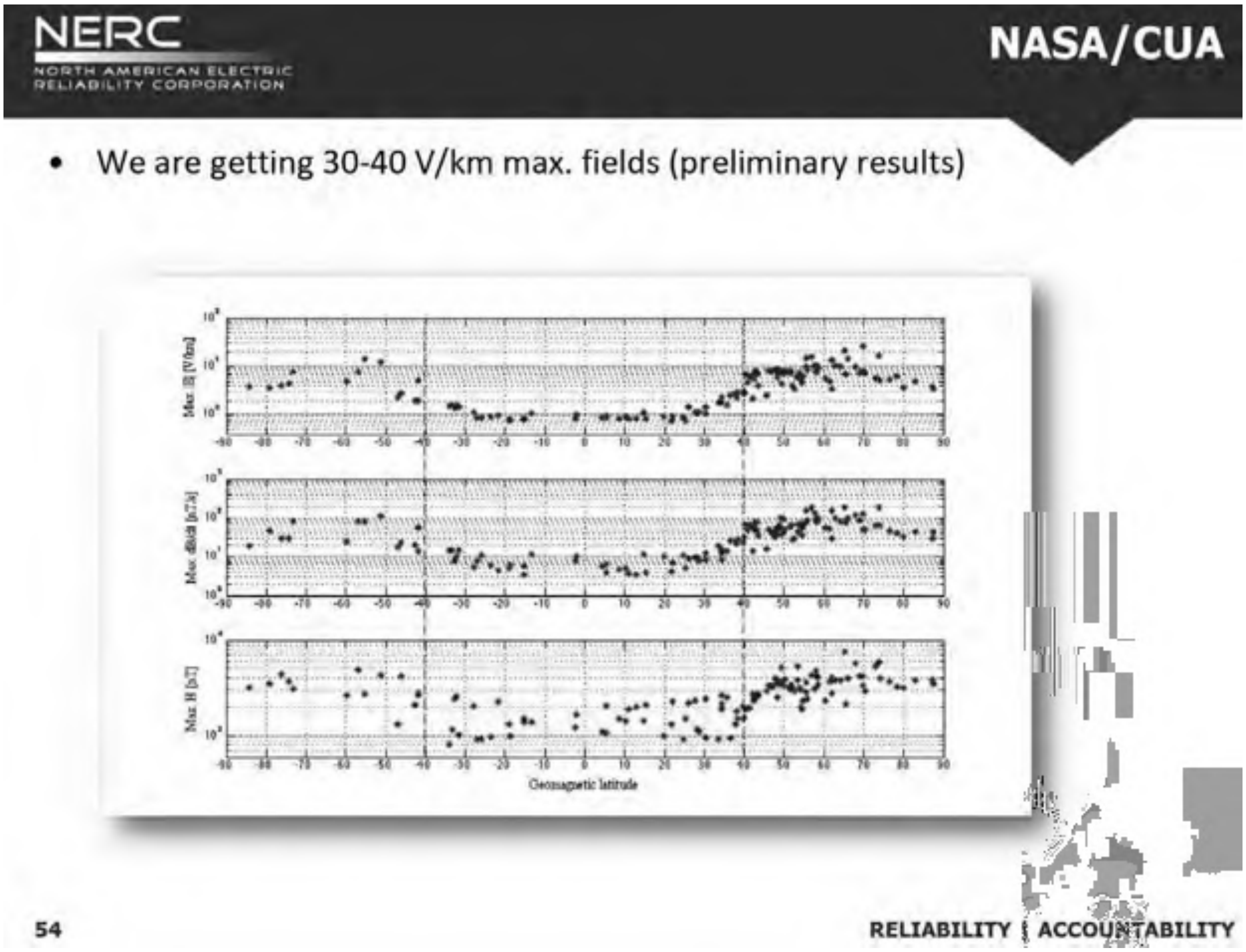

Figure 4: Slides from NERC GMD Task Force presentation

When GMD Task Force Team 3 initiated drafting of the "Application Guide" and gave a contemporaneous presentation in Vancouver in July 2013, the reference geoelectric field had been downwardly adjusted to a range between 5 V/km and 20 V/km. At this point the "Science

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[24] See presentation slides of "GMD Task Force Phase 2 Ken Donohoo, Task Force Chairman, In-Person Meeting, February 25-27, 2013", p. 52 and other relevant material available at http://www.nerc.com/docs/pc/gmdtf/MeetingSlides_25Feb_final.pdf . Space weather scientists on the "Current Science Team" at the time of the 30-40 V/km geoelectric filed estimate included A. Pulkkinen (NASA/CUA), W. Murtagh (NOAA), C. Balch (NOAA), J. Gannon (USGS), D. Boteler (NRCan), R. Pirjola (NRCan), D. Baker (U. of Colorado), and A. Thomson (BGS/EURISGIC).

[25] See "Response to NERC Request for Comments on Geomagnetic Disturbance Planning Application Guide," Resilient Societies, Comments to NERC GMD Task Force, August 9, 2013, filed as a record of standard-setting, p. 65

Working Group" of Team 3 consisted of only two scientist representatives, one from NASA/CUA and another from Oregon State University:[26]

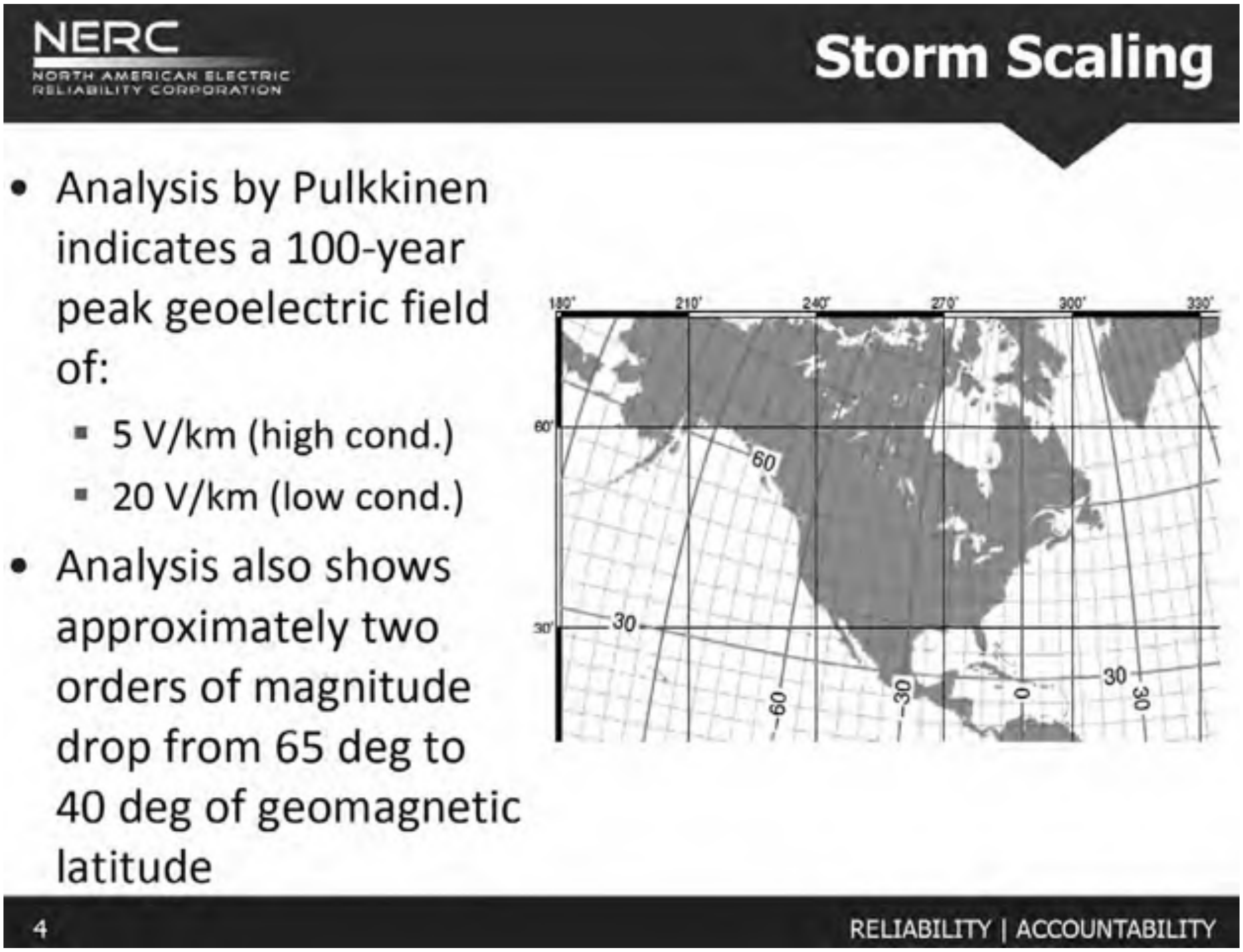

Figure 5: NERC Storm Scaling model slide

By April 2014, the Standard Drafting Team had set an even lower reference storm peak value of 5.77 V/km. approximately one fifth of the lower range preliminary estimate of 30V/km. At this time, only one scientist representative, an employee of the NASA Goddard Space Flight Center, remained on the Standard Drafting Team. The remaining team members were employed by

[26] See "Team 3 Update, Application Guide Randy Horton, Southern Company, GMD Task Force Meeting, July 25, 2013" in the presentation slides for "GMD Task Force Phase 2, Ken Donohoo, Task Force Chairman, In-person meeting, July 25-26, 2013", available at http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/presentations_all.pdf , p. 2, p. 4 and other relevant material.

PJM Interconnection, Southern Company, Georgia Transmission Corporation, Dominion Resource Services, NextEra Energy, Hydro One Networks, and American Electric Power.[27]

The apparent preference for a single scientist on the Standard Drafting Team, who might seek to espouse his own published hypotheses on spatial averaging of geoelectric fields, but not necessarily represent a scientific consensus on storm modeling, is not consistent with the "balancing" and "transparency" requirements of the Energy Policy Act and the NERC by-laws. In the aftermath of the October 2003 U.S.-Canadian Blackout, the primary purpose of developing reliability standards under Section 215 of the Federal Power Act is to *improve the reliability of the bulk power system;* this purpose is not achieved by use of unconfirmed scientific hypotheses.

In the final standard, the Standard Drafting Team set the reference peak geoelectric field to 8 V/km, upwardly adjusted from 5.77 V/km by an "implicit safety margin" of 25%. Given the storied history of the severity of GMD in 1-in-100 Year reference storm peak value, FERC was right to address this issue in the GMD NOPR:

> 36. To address this issue, the Commission proposes to direct NERC to develop modifications to the Reliability Standard so that the reference peak geoelectric field amplitude element of the benchmark GMD event definition is not based solely on spatially-averaged data. For example, NERC could satisfy this proposal by revising the Reliability Standard to require applicable entities to conduct GMD Vulnerability Assessments and thermal impact assessments using two different benchmark GMD events: the first benchmark GMD event using the spatially-averaged reference peak geoelectric field value (8 V/km) and the second using the non-spatially averaged peak geoelectric field value found in the GMD Interim Report (20 V/km).

However, it would be a mistake for FERC to determine that applicable entities might conduct two GMD Vulnerability Assessments, one at 8 V/km and another at 20 V/km, relying on the engineering judgment of the entities. Instead, FERC should order GMD Vulnerability

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[27] See "NERC Standard Drafting Team Rosters, May 2014,"available at http://www.nerc.com/pa/Stand/Documents/Standard_Drafting_Team_Rosters_March_2014.pdf , p. 21. The one remaining scientist from outside the electric utility industry espoused modeling based on Finland and other Northern European IMAGE geomagnetic sites; in lieu of modeling of the North American geomagnetic network and with GIC readings from North America. The foreseeable result is a proposal that FERC adopt a standard without a technical basis confirmed by scientific consensus.

Assessments at a single peak value set for technically justified protection of the public from solar storm blackouts. There cannot be two correct reference peak geoelectric field values; if there is doubt, FERC should mandate the higher value with greater safety for the public.

Geographic Footprint and Issue of Spatial Averaging

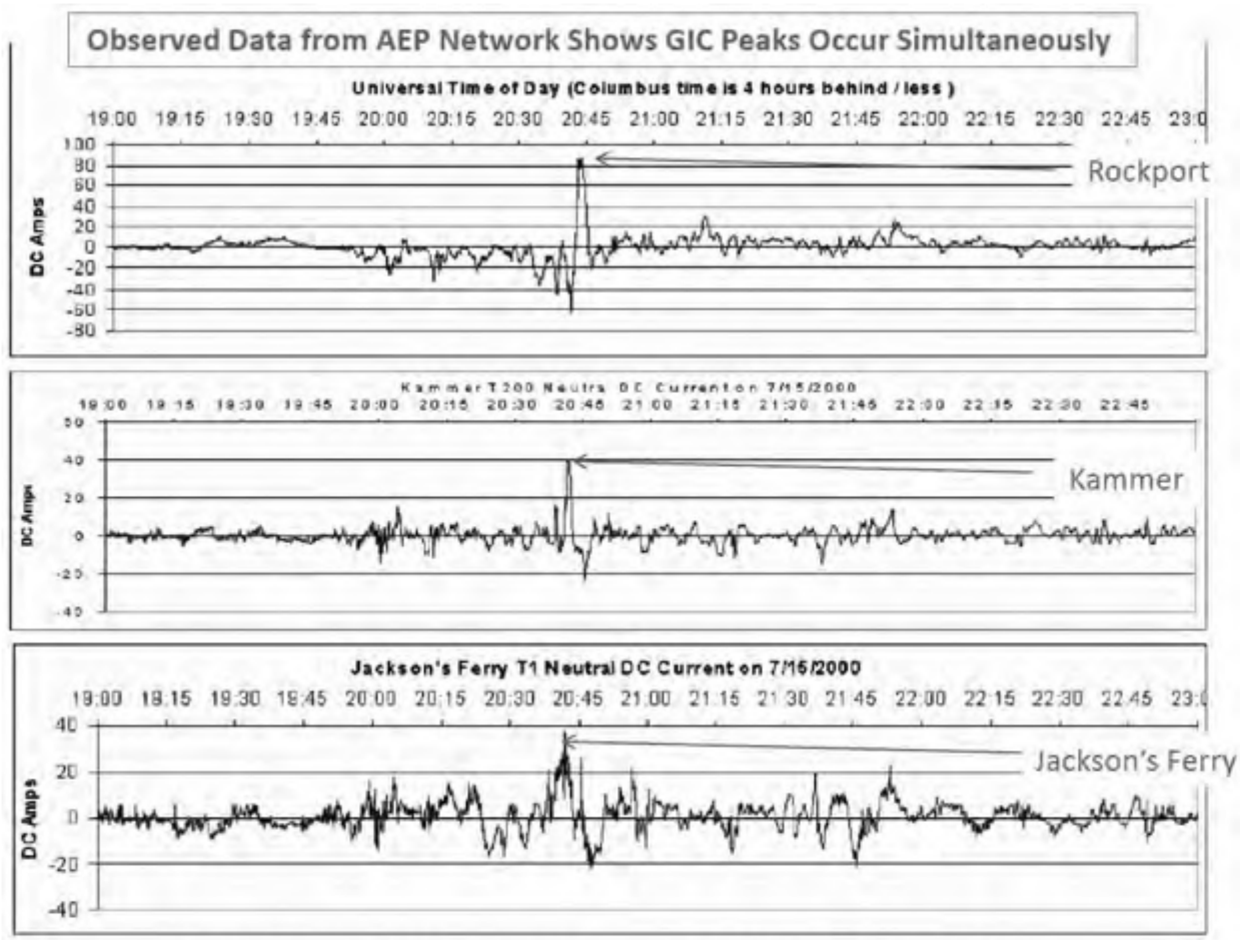
FERC had appropriate concerns about the use of spatial averaging to set the Benchmark GMD Event, proposing in the GMD NOPR (p. 24):

> 39. In particular, we propose to direct that NERC submit informational filings that address the issues discussed below. In the first informational filing, NERC should submit a work plan indicating how NERC plans to: (1) further analyze the area over which spatial averaging should be calculated for stability studies, including performing sensitivity analyses on squares less than 500 km per side (e.g., 100 km, 200 km); (2) further analyze earth conductivity models by, for example, using metered GIC and magnetometer readings to calculate earth conductivity and using 3-D readings; (3) determine whether new analyses and observations support modifying the use of single station readings around the earth to adjust the spatially averaged benchmark for latitude; and (4) assess how to make GMD data (e.g., GIC monitoring and magnetometer data) available to researchers for study. We propose that NERC submit the work plan within six months of the effective date of a final rule in this proceeding. The work plan submitted by NERC should include a schedule to submit one or more informational filings that apprise the Commission of the results of the four additional study areas as well as any other relevant developments in GMD research. Further, in the submissions, NERC should assess whether the proposed Reliability Standard remains valid in light of new information or whether revisions are appropriate.

The Benchmark Geomagnetic Disturbance (GMD) Event whitepaper authored by the NERC Standard Drafting Team proposed a conjecture that geoelectric field “hotspots” take place within areas of 100-200 kilometers across, but that these hotspots would not have widespread impact on the interconnected transmission system. Accordingly, the Standard Drafting Team averaged geoelectric field intensities downward to obtain a “spatially averaged geoelectric field amplitude” of 5.77 V/km for a 1-in-100 year solar storm. This spatially averaged amplitude was then used for the basis of the “Benchmark GMD Event”.

Even the limited amount of publicly available GIC and magnetometer data shows the NERC “hotspot” conjecture is inconsistent with real-world observations and therefore the “Benchmark GMD Event” is not technically justified. Figures A and B below show simultaneous

GIC peaks observed at three transformers up to 580 kilometers apart, an exceedingly improbable event if NERC's "hotspot" conjecture were correct.



GIC Peaks All Observed at Same Time: ~22:42 UT July 15, 2000

Figure 6: American Electric Power (AEP) Geomagnetically Induced Current Data Presented at February 2013 GMD Task Force Meeting

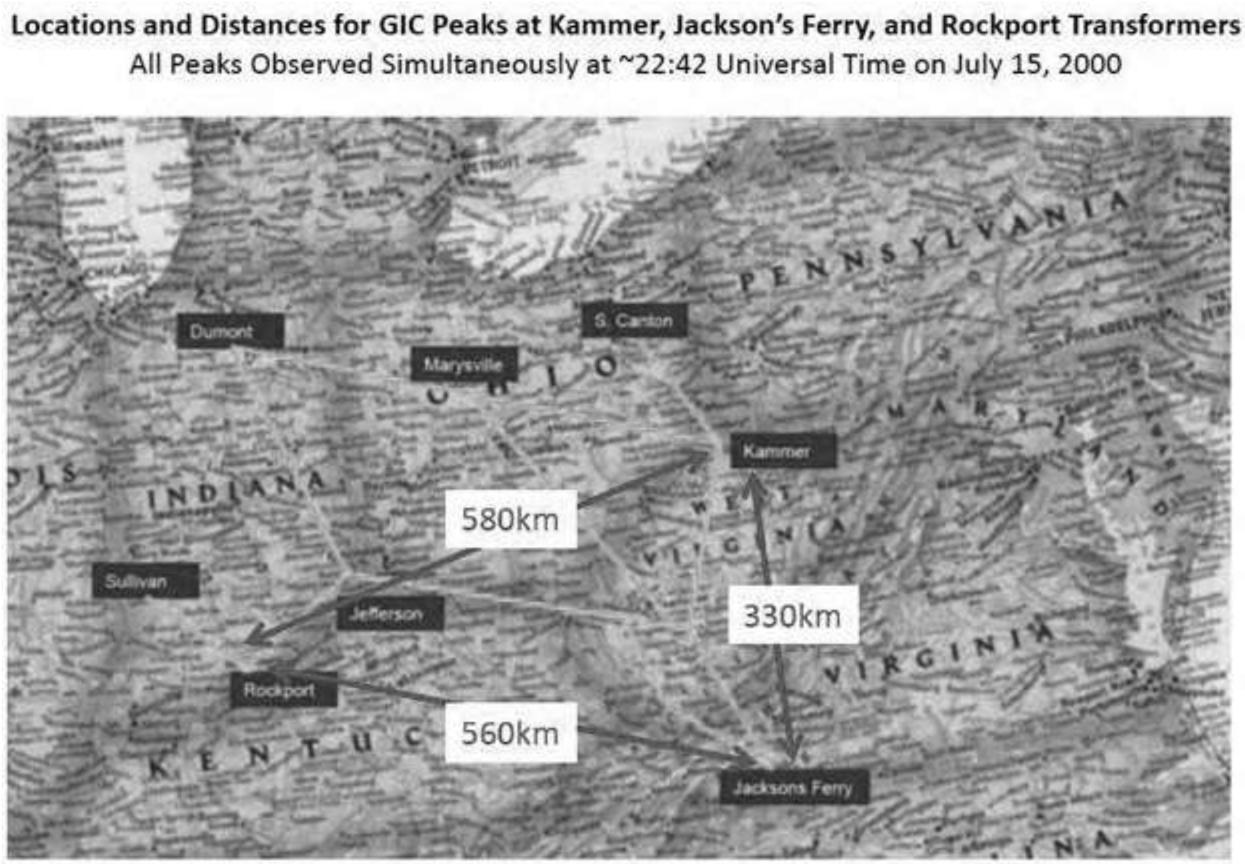
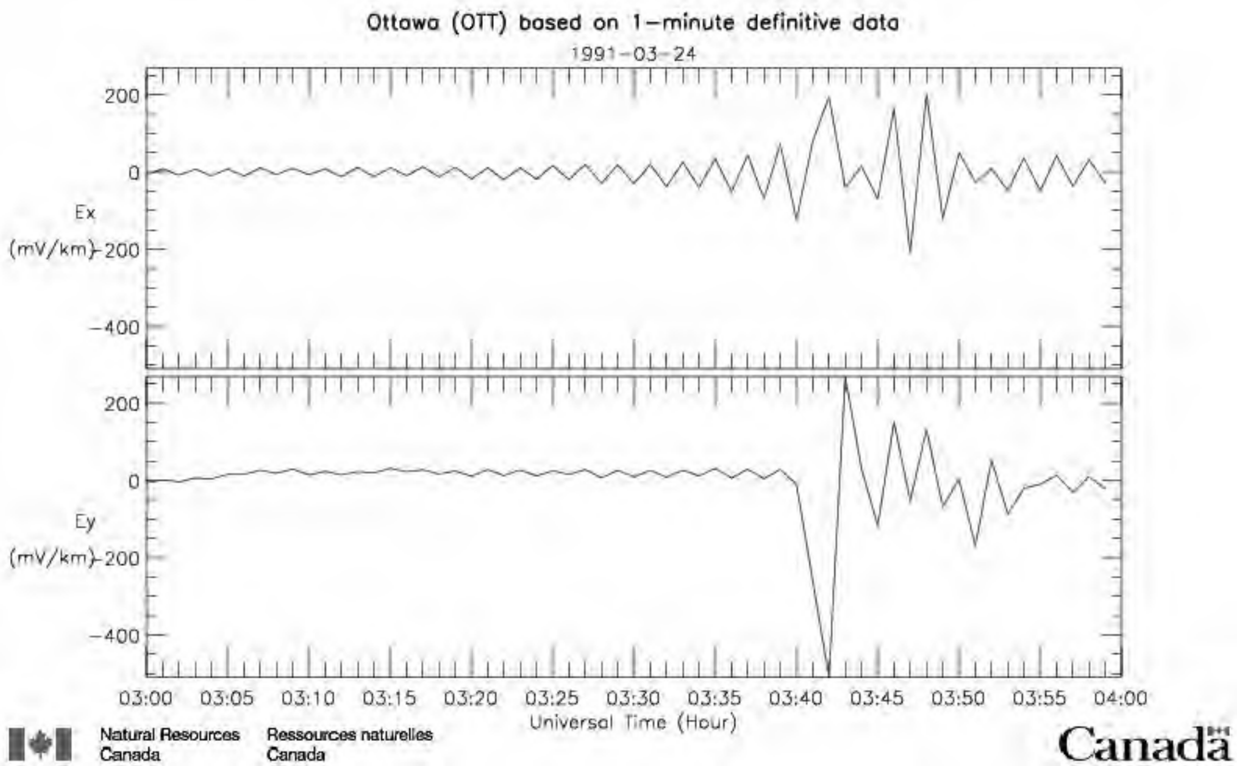


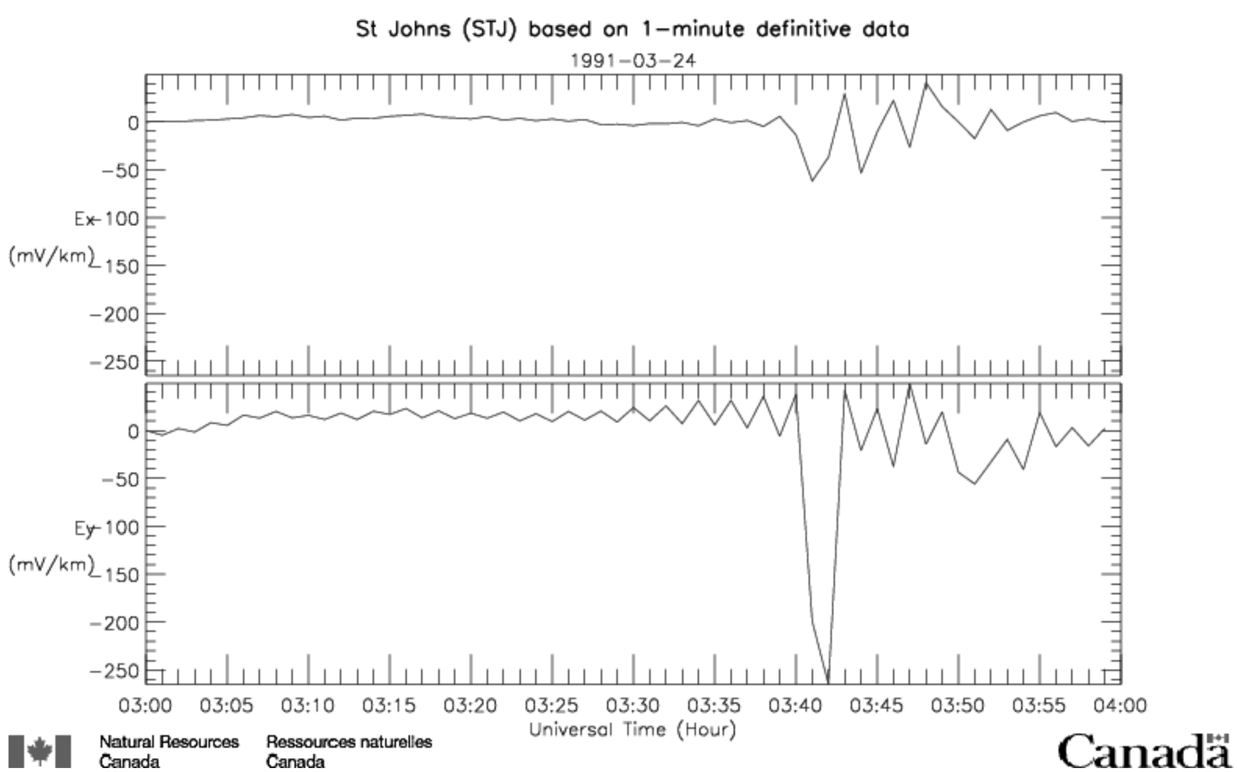
Figure 7: Location of Transformer Substations with GIC Readings on Map of States within AEP Network

According to Faraday's Law of induction, geomagnetically induced current (GIC) is driven by changes in magnetic field intensity (dB/dt) in the upper atmosphere. If dB/dt peaks are observed simultaneously many kilometers apart, then it would follow that GIC peaks in transformers would also occur simultaneously many kilometers apart, affecting reliable operation of the Bulk Power System.

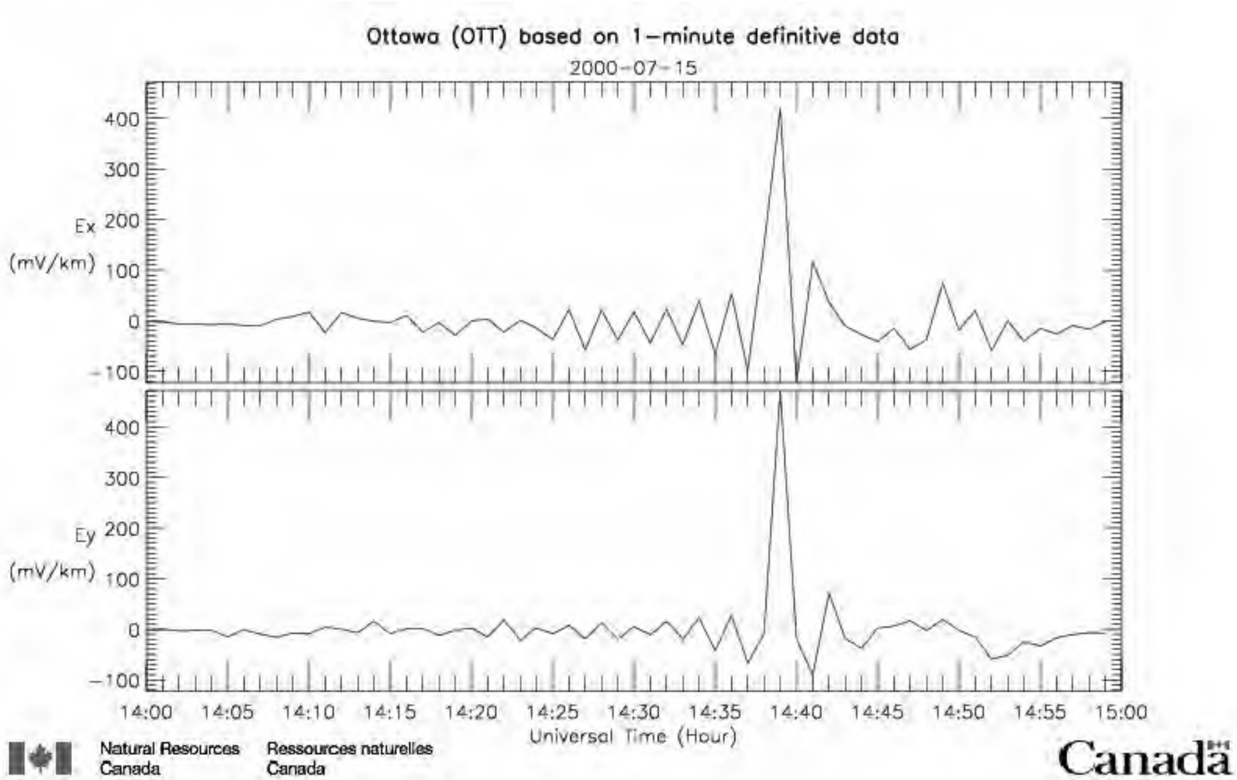
Natural Resources Canada has a plotting service on their website where geoelectric fields for past storms are estimated at Ottawa and St. John observatories using dB/dt readings. Even cursory examinations of past solar storms show that peaks in estimated geoelectric field occur simultaneously at these two observatories 1,760 kilometers apart. Examples are presented below for three significant storms.

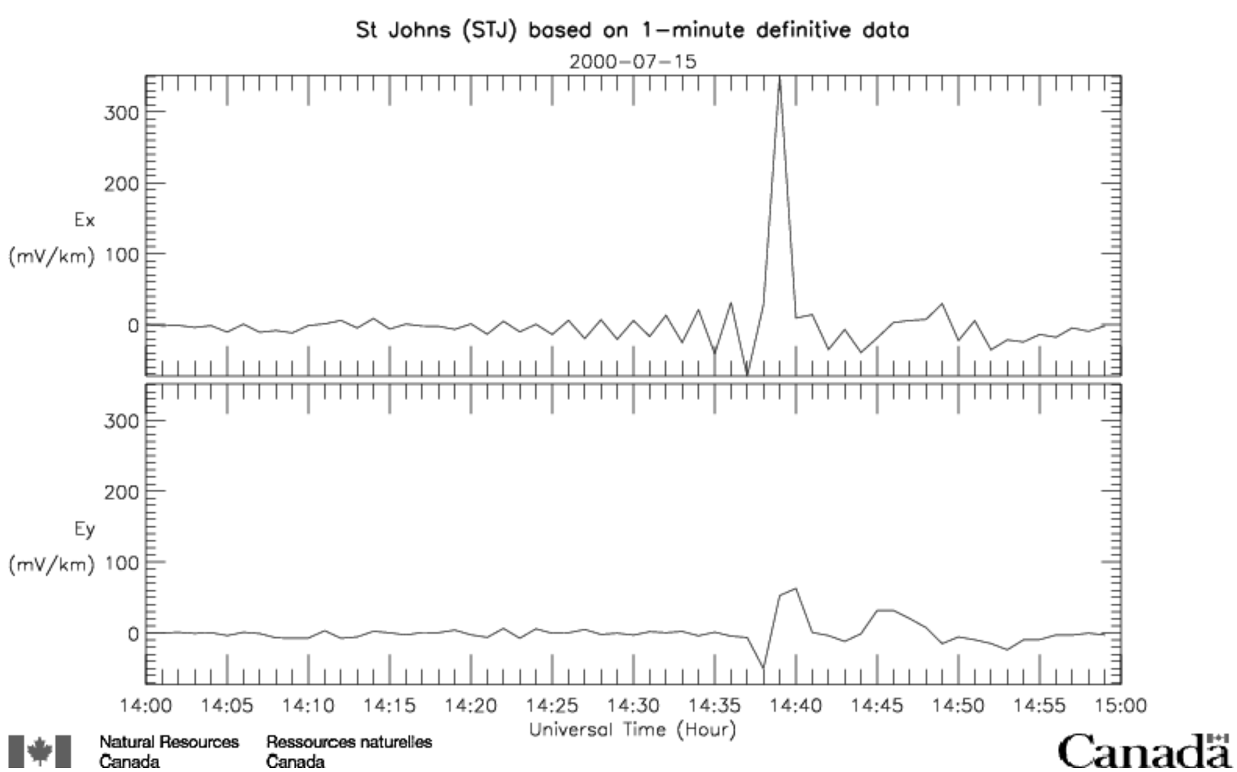
Simultaneous Geoelectric Field Troughs at 03:42 UT on 1991-03-24





Simultaneous Geoelectric Field Peaks at 14:39 UT on 2000-07-15





Simultaneous Geoelectric Field Troughs at 00:53 UT on 2001-03-31

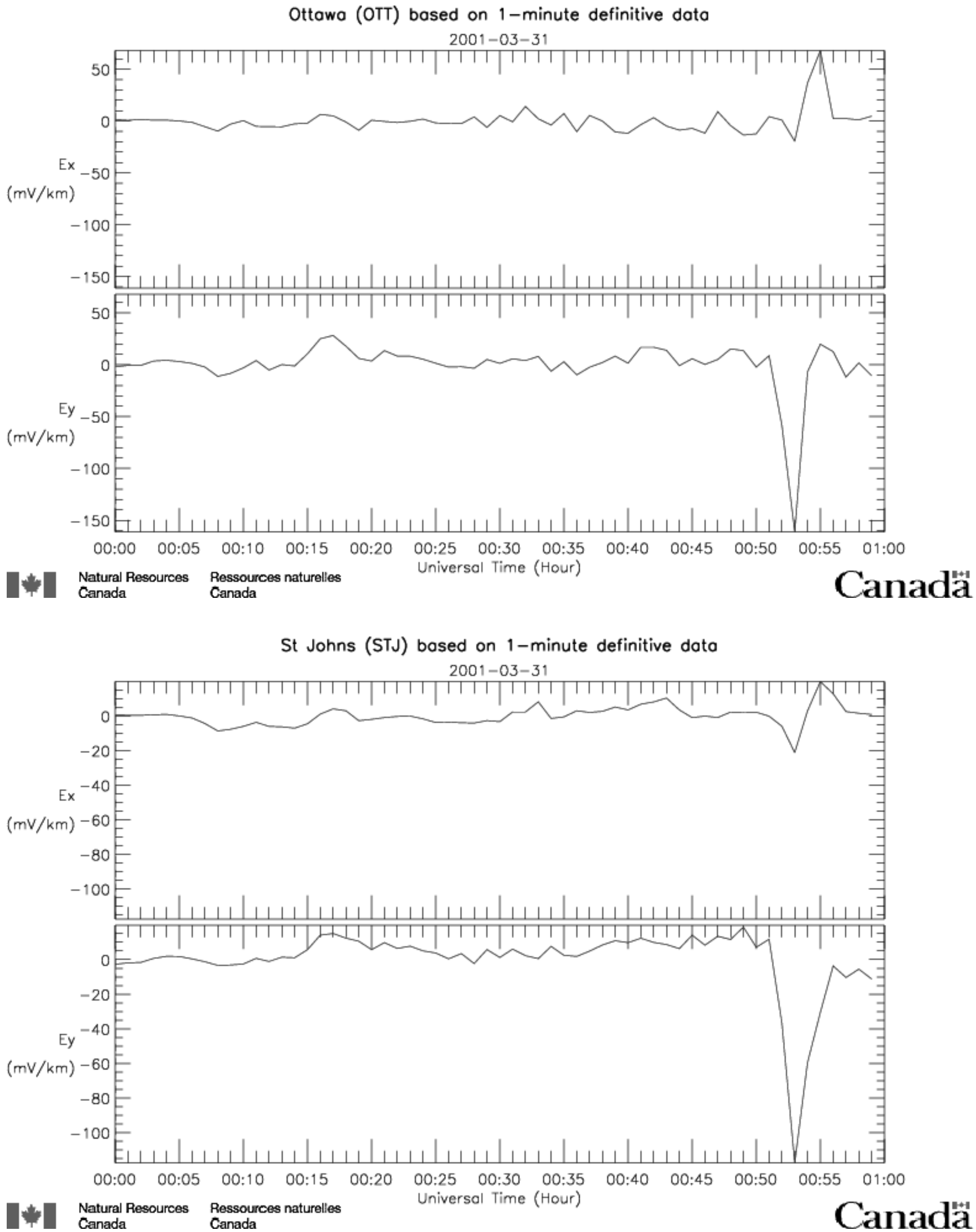


Figure 8: Synchronous Geoelectric field peaks and troughs in distant magnetometers

The weight of real-world evidence even now available shows the NERC "hotspot" conjecture to be erroneous.[28] Simultaneous GMD impacts can and do occur over wide areas. Greater collection and availability of GIC data at a variety of dispersed locations is likely to further confirm the NERC Benchmark GMD Event is technically unjustified and without "strong technical basis."

GMD Intensity and Variance with Geomagnetic Latitude

In the GMD NOPR (p. 23), the Commission appropriately recognized studies indicating that GMD events could have impacts on lower latitudes:

> "37. The Commission also seeks comment from NERC and other interested entities regarding the scaling factor used in the benchmark GMD event definition to account for differences in geomagnetic latitude. Specifically, the Commission seeks comment on whether, in light of studies indicating that GMD events could have pronounced effect on lower geomagnetic latitudes, a modification is warranted to reduce the impact of the scaling factors."

On FERC's own docket for the Stage 1 GMD Standard, there is a description of a transformer failure at a low-latitude location in Contra Costa, California due to GIC:

> It is widely known that the Salem Nuclear plant GSU transformer failure (due to winding heating) was caused by a combination of design of the transformer and its vulnerability to GIC-exposure. This was a Westinghouse manufactured single phase shell-form transformer. However, within the IEEE Survey, one other transformer failure during the March 1989 storm was also declared as being due to GIC. This had not been widely known and was overlooked until a careful review of the data in this survey was assembled in this report. This particular transformer failure was reported as being at the Contra Costa Bank 6 GSU transformer by Pacific Gas and Electric.[29]

Multiple published studies have demonstrated GMD impacts at low latitudes and levels of GIC below the thermal assessment threshold of 75 amps in the standard, including "Transformer failures in regions incorrectly considered to have low GIC-risk," "Storm sudden commencement events and the associated geomagnetically induced current risks to ground-based systems at

[28] Resilient Societies had not as yet had time to analyze the Kappenman (Storm Analysis Consultants) and Birnbach (Advanced Fusion Systems) forensic review of how the GIC "hotspot" conjecture appeared, was then reformulated, and later surfaced with diminished justification for a new GMD Benchmark Event. The NERC ballot body may not have been fully informed and not enabled to understand before voting upon a standard for hardware protection lacking scientific consensus.

[29] "Comments of the John G. Kappenman, Storm Analysis Consultants," FERC Docket No. RM14-1-000, March 24, 2014.

low-latitude and mid-latitude locations," and "Geomagnetically induced currents in the Southern African electricity transmission network."[30,31,32] In light of this experience and published work, it would be imprudent and without "strong technical basis" for FERC to allow the aggressive geomagnetic latitude scaling factors of the Benchmark GMD Event.

Electric System Boundaries and Coastal Effects

Why does the model for the NERC Benchmark GMD Event systematically under-estimate geoelectric fields (volts per kilometer), or amps per phase, compared to empirical measurements? If a standard-seeking goal is to minimize the facilities and regions of the Bulk Power System that would be responsible to install hardware mitigation, then one tactic would be to eliminate entire classes of risks from benchmark modeling.

A candidate for NERC benchmark modeling that is conspicuously absent in the NERC standard is the coastal effect. The overall result of this purposeful exclusion is to down-rate modeled risks of solar storms in coastal regions of the Continental United States (CONUS) and Canada. Excluding the State of Alaska, fully 39 percent of the U.S. population resides in coastal counties that comprise just 10 percent of the landmass of the CONUS. These coastal counties with extended coastlines account for 48% of the Gross National Product of the United States. So the "coastal zone" is economically important.[33]

And the "coastal effect" or "coastal effects" play a significant risk-elevating role in scientific assessment of GMD vulnerabilities of the Bulk Power System, which has significant numbers of nuclear power plants and large load centers in the coastal zone.

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[30] "Transformer failures in regions incorrectly considered to have low GIC-risk," Gaunt, C.T., and G. Coetzee, Proceedings of Power Tech, July 15, 2007, Lausanne, Switzerland.
[31] "Storm sudden commencement events and the associated geomagnetically induced current risks to ground-based systems at low-latitude and midlatitude locations," John G. Kappenman, Space Weather, Volume 1, Issue 3, December 2003.
[32] "Geomagnetically induced currents in the Southern African electricity transmission network," Koen, J. and Gaunt, T., Power Tech Conference Proceedings, 2003 IEEE Bologna , vol.1, no., pp.7 pp. Vol.1, 23-26 June 2003.
[33] For an overview of the coastal economy, see the NOAA State of the Coast website, found at www.stateofthecoast.noaa.gov/coastal_economy/welcome.html.

Three sets of modeling considerations are intertwined when modeling the "coast effect." These are:

- **Edge effects of electric transmission systems**. Network modeling indicates that GIC tends to enter transmission systems from the edges; hence neutral ground blocking devices can be effective at these locations.
- **Boundary conditions associated with oceanic and land mass interactions**.
- **Higher conductivity of salt water adjacent to electric grid facilities**

The physical principles underlying these three interacting effects are described in published literature but not fully confirmed by empirical measurements. The so-called "coastal effect" was first identified as affecting electric grids nearly ninety years ago in Australia. Four geomagnetic storms recorded at seven separate observatories led to postulation of a "coastal effect" by the year 1926-27.[34] Albert Price advanced physics modeling of geomagnetic induction in 1973.[35] Thereafter, J. L. Gilbert of Metatech published in 1975 a model of interactions of geomagnetic storms at boundaries between oceans and landmasses. Gilbert estimated a coastal effect of about 2X compared to inland geoelectric fields.[36] Boteler and Prijola also published work on oceanic geoelectric fields.[37] Research on transoceanic cable systems modeled the so-called Dirichlet boundary condition, which has the effect of increasing GIC on the land side of various ocean-land boundaries. Some literature indicates that the "coastal effect" differs along different coasts and may relate to deeper subsurface magnetotelluric anomalies.[38]

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[34] Baird, H. F. "A preliminary investigation of some features of four magnetic storms recorded at seven observatories," M. Sc. Thesis, University of New Zealand, Canterbury College, Christchurch, 1927.
[35] Price, A.T., "The Theory of Geomagnetic Induction," T., "The Theory of Geomagnetic Induction," Physics of the earth and Planetary Interiors 7:227-233 (1973).
[36] Gilbert, J.L., "Modeling the effect of the ocean-land interface on induced electric fields during geomagnetic storms," Space Weather 3: S04A03 (1975).
[37] "Magnetic and electric fields produced in the sea during geomagnetic disturbances," Pure Appl. Geophys. 160: 1695-1716. (2003).
[38] See references 3, 4, and 5 in the U.S. Geological Survey submission of July 24, 2015 for additional references on the "coastal effect."

In the past two decades, measurement and modeling of the coastal effect that is also interrelated with end-of-line conditions has led to a broad range of estimates of impact upon the vulnerability of critical electric grid equipment.

At the high end of the range for "coastal effect" is the Atmospheric Environmental Research (AER) modeling performed for Lloyd's, in the context of an extensive electrical equipment claims databasefor North America that is not publicly accessible. The AER study asserts that the coastal effect increases exponentially near the coast.[39] Since claims data is likely to reflect the interactions of three variables (end of line effects; and ocean-land boundary effects, and ground conductivity), any model developed with the purpose of explaining empirical claims data may overstate the actual "coast effect" component.

More recently, Dr. David Boteler of Natural Resources Canada has participated in two reviews of the "coastal effect." One is a Chapter in a book (2014) under the editorship of Carol Schrijver on geomagnetic effects on the electric grid. This chapter cites a year 1987 study (Wannamaker) that estimates the coastal effect as being about a factor of 7.3X.[40]

In a study commissioned by the Electric Power Research Institute (EPRI), Dr. Boteler concluded in year 2013 that the best estimate for the "coastal effect" was a factor of 4X. Overall, we see estimates for the "coastal effect" and associated end-of-line and electric boundary effects between the range of 2X (Gilbert, 1975) and 7X (Wanamaker, 1987).

Finally, we should bring to the Commission's attention the significance of a careful statistical analysis of the Zurich Re claims database relating to the electric utility industry. This study does not specifically estimate a "coastal effect" but it may help to explain a key finding: unlike the NERC GMD Task Force and Standard Drafting Team, analysts of the Zurich Re insurance claims

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[39] See the Lloyd's-AER Report of June 2013, included as Reference Document No. 11. Sec. 5.3 at p. 10 states: "Coastal regions experience an enhancement in the surface electric field due to the high conductivity of seawater. This can be thought of as the seawater carrying extra charge, and the nearby, grounded, transformers provide a path for the current to flow. The enhancement from the coast effect increases exponentially towards the coast." Some "coastal counties" are shown on Fig. 4, indicating a relative risk factor for high risk counties as more than 1000X times low risk counties. "The regions with the highest risk are along the corridor between Washington, D.C. and New York City. Other high-risk regions are the Midwest and regions along the Gulf Coast." Lloyd's-AER Report at p. 10.

[40] See Reference Document No. No. 9, Dr. Boteler's chapter 4, cites Wannamaker (1987).

database which covers about 8 percent of electric utility insurance in the U.S. find no statistically significant relationship between geographic or geomagnetic latitude and the frequency and amount of insurance claims.[41] This one study casts serious doubt upon the validity of the so-called *Alpha factor* in the NERC Benchmark GMD Event model. Why is there no statistically significant correlation with geomagnetic latitude for the claims database? With a possible coastal effect of 2X to 7X, insurance claims along the Southeast Coast, the Florida Coast, and the Gulf of Mexico could counter or mask a smaller but valid *Alpha Factor.*

For public policy purposes, and for deciding whether to require hardware protective equipment for critical transformers in coastal zones, does it matter if there are three sets of physical principles that are difficult to untangle? If a NERC Benchmark Model exempts most every coastal zone facility, when empirical claims evidence indicates these facilities are at particularly aggravated risk of loss or damage, there may be reasons to require hardware protection, perhaps decades before physicists are able to sort out all the interactions of electric grid behavior in the coastal zone. [42]

Finally, it is notable that most of the transformer failures during moderate solar geomagnetic storms are within the “coastal zone” including: Maine Yankee in Wiscasset, Maine; Seabrook Station along the New Hampshire coast; and Salem-1 and Salem-2 nuclear power plants adjacent to Delaware Bay.

From the evidence adduced, it is apparent that it would be arbitrary and capricious for the Commission to approve the NERC Benchmark GMD Event model and associated standard elements without the consideration of a “coastal effect.” Parties located near high-latitude coastal regions, such as Resilient Societies headquartered in New Hampshire and dependent on the Seabrook Station nuclear power plant, would be directly and materially affected by

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[41] See Schrijver, Dobbins, Murtagh, and Petrinec, in Space Weather (2014), Reference Document No. 13.

[42] A complication in this effort relates to the unavailability of some assessments of the “coastal effect” upon the transmission of electric currents from subsurface telecommunications cables that serve national security missions. Some of the best-instrumented ocean-to-land systems are telecommunication systems; these can show the attenuation in volts per kilometer as a cable extended from the near-coast to the interior, away from the coast. It is possible that FERC could seek technical assessment support from NSTAC, a National Telecommunications Advisory system that advises the President on national telecommunications requirements. An NSTAC Report on Telecommunications and Electric Power (2006) is included in Reference Document No. 14 in our filings.

omission of consideration of a coastal effect in the NERC standard and associated Benchmark GMD Event.

Vibration Effects at Lower GIC Thresholds than Thermal Effects

Another category of hazards to critical grid equipment is the effect of vibrations upon high voltage transformers. One aspect of vibration is known as *magnetostriction;* this effect can cause shaking and noise within high voltage transformers. Importantly, the vibrations occur at relatively lower magnitude geomagnetic storms than the magnitudes required to overheat high voltage transformers. Hence, in a severe solar geomagnetic storm, if vibrational effects are not modeled, the model may under-predict the percentage of critical equipment that is damaged or destroyed.

We first discovered an event that involved vibration effects and transformer damage by comparing a database of solar geomagnetic storms with Nuclear Regulatory Commission reports on transformer fires or losses. At Seabrook Station on November 8-9, 1998, there was a solar geomagnetic storm with a North-to-South storm overtaken by a South-to-North storm. These storm interactions can cause a "sudden impulse" even in a storm of moderate magnitude. A stainless steel bolt shook loose into the low voltage winding; and on Nov. 10, 1998, the low voltage windings melted; the transformer was shut down; and Seabrook Station had a 12.2-day outage.

First, Seabrook engineers claimed the damage could not have been caused by a solar storm, because the damage was at the low voltage winding, not the high voltage winding. Pictures of a Salem-1 transformer on March 13, 1989 also indicated the melted windings were at the low voltage end of the transformer. Next, Seabrook engineers claimed the loss was due to a mis-manufactured 4-inch stainless steel bolt. But why did the bolt stay in place for about 3000 days of transformer operation, and only fail during a sudden impulse GMD event?[43] Finally, the NERC

[43] See Harris, "W.R. Seabrook Station Unit 1: Damage to Generator Step-Up Transformer Identified 10 November 1998 Immediately Following Geomagnetic Storm Shocks of November 7-9, 1998,"January 19, 2012, provided to NERC GMD Task Force January 2012, available at http://www.resilientsocieties.org/images/AD12-13-000_Resilient_Societies_Seabrook_Station_GMD_April_25_2012.pdf, last accessed July 27, 2015.

GMD Standard Drafting Team proclaimed this event was merely “anecdotal” as a basis to exclude the entire category of vibration hazards from the NERC Benchmark Model.

Where might non-anecdotal data be found to confirm that vibrational hazards are systematic and widespread during GMD events? The answer: NERC’s own website, where the “March 13, 1989 Geomagnetic Disturbance” report published in 1990 identifies noise or vibration in at least seven separate locations during the 13 March 1989 solar storm.[44] Did NERC ‘s Standard Drafting Team cite their own report in considering vibrational impacts? They did not.

For references to an extensive theoretical and acoustical modeling literature on vibrational impacts on critical equipment, see Resilient Societies Level 1 Appeal documents of Jan 4-5, 2015.[45]

Finally, the GMD Task Force leadership attended experiments at Idaho National Laboratory (INL) in year 2013, together with officials from DTRA DOD and a member of the Resilient Societies’ Board. For a science experiment that was purposeful and non-anecdotal, an INL Team supervised by Scott McBride injected DC power into a 138 kV transformer, and observed the vibration of the transformer; when power was off, the vibrations ceased. Then INL staff attached a neutral ground blocker. When the blocker was turned on, the vibrations ceased; when the neutral ground blocker was turned off, the vibrations returned.

In December 2013, Mr. McBride commented on the recent experiment showing vibration effects on an unprotected transformer, and the protections afforded by neutral blocking devices. Mr. McBride remarked: “Watching a 150,000-pound transformer visibly vibrating and

[44] See 1990 NERC Compilation on March 13, 1989 Geomagnetic Disturbance at p. 57ff: Event 5 Noise SC Edison, Bishop, CA; Event 19, Noise, PJM Calvert Cliffs; Event 66, Noise PJM Calvert Cliffs; Event 77, Noise Portland GE, Oregon; Event 84, Noise PJM Calvert Cliffs; Event 90, Noise SC Edison Mira Loma; Event 105, Noise BPA Rose substation; Event 114, Nose WEP Point Beach, WI.

[45] For multiple references on vibrational models and vibrational impacts, readers should utilize click-through to the NERC Level 1 and Level 2 Appeals files, in Reference Document No. 5, submitted with this Comment filing.

moving along the ground during a simulated solar event (ground-induced current) is a sobering sight."[46]

Altogether, vibrational impacts are important components of GMD hazards to high voltage transformers. The Commission should remand the NERC standard to include, among other considerations, vibrational impacts and options for protective equipment against vibration.

Geomagnetic Field Orientation

The Commission sought comment from NERC in the GMD NOPR on geomagnetic field orientation (p. 27):

> The Commission seeks comment from NERC as to why qualifying transformers are not assessed for thermal impacts using the maximum GIC-producing orientation. NERC should address whether, by not using the maximum GIC-producing orientation, the required thermal impact assessments could underestimate the impact of a benchmark GMD event on a qualifying transformer.

We also wish to comment that GMD Vulnerability Assessments should contain a case for "maximum geomagnetic field orientation" and that any studies of transformer vulnerability, harmonic production, reactive power consumption, voltage collapse, equipment tripping, vibration impact, and other Bulk Power System vulnerabilities should be conducted using amperage from the maximum orientation.

Technically Unjustified Transformer Assessments

Screening Criterion for Transformer Thermal Impact Assessments

The GMD NOPR (p. 25) recites Reliability Standard TPL-007-1, Requirement R6, which proposes that transformers with an effective GIC of less than 75 A per phase during the Benchmark GMD Event would be exempt from thermal screening:

> Proposed Reliability Standard TPL-007-1, Requirement R6 requires owners of transformers that are subject to the proposed Reliability Standard to conduct thermal analyses to determine if the transformers would be able to withstand the thermal effects associated with a benchmark GMD event. NERC states that transformers are exempt

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[46] See Keith Arterburn, "Advancing a National Electric Grid Reliability Test Bed," Idaho National Laboratory, at https://inlportal.inl.gov/portal/server.pt/community/newsroom/257/feature_story_deetails/1269?featurestory=DA_607328.

> from the thermal impact assessment requirement if the maximum effective GIC in the transformer is less than 75 A/phase during the benchmark GMD event as determined by an analysis of the system. NERC explains that "based on available power transformer measurement data, transformers with an effective GIC of less than 75 A per phase during the Benchmark GMD Event are unlikely to exceed known temperature limits established by technical organizations.

The 75 amp per phase Screening Criterion for transformer thermal impact assessment is perhaps the most egregious defect in all of Standard TPL-007-1, as this important limit is almost entirely without technical basis. We took the time to carefully review the NERC whitepaper "Screening Criterion for Transformer Thermal Impact Assessment," as well as the key references, and we trust that FERC technical staff will re-review these documents after reading our comment. Here is a partial list of major defects in the Screening Criterion:

1. The Screening Criterion is a mathematically modeled construct without actual testing of any transformers under full load at 75 amps injected direct current.
2. The NERC whitepaper makes the claim near the top of page 4 "The 75 A per phase screening threshold was determined using single-phase transformers, but is applicable to all types of transformer construction." This claim is absurd on its face, even to nontechnical laypeople—it is like an automobile manufacturer conducting crash tests on three models of sedans and then claiming the results can be used to exempt all makes and models from further crash testing.
3. The NERC whitepaper makes the disclosure on the top of page 5 "The screening thermal model is based on laboratory measurements carried out on 500/16.5 kV 400 MVA single-phase Static Var Compensator (SVC) coupling transformer." A "coupling transformer" is used to support reactive power rather than transmit real power and therefore its test results are not applicable, except as a hypothetical construct.
4. On the top of page 5, the NERC whitepaper discloses that "Temperature measurements were carried out at relatively small values of GIC (see Figure 2)." In fact, when the whitepaper references with the more detailed test procedures were checked, we found that the test in Reference 2 was conducted under "no-load conditions" at 5 amps for 2 hours, followed by a maximum of 16.7 amps for only one minute. This unrealistic test

was conducted far below the 75 amp Screening Criterion the standard proposes.[47] Reference 2 for the NERC Screening Criterion whitepaper helpfully discloses the reason more rigorous transformer tests under injected direct current conditions are not performed—"***for fear of damaging the transformer***" (emphasis added). [48]

5. On the top of page 4, the NERC Screening Criterion whitepaper discloses that "Winding hot spots are not the limiting factor in terms of hot spots due to half-cycle saturation, therefore the screening criterion is focused on metallic part hot spots only." In fact, winding hot spots have been the failure mode in several major incidents of transformer GIC damage, the most notable example being the Salem 1 nuclear plant Phase "A" and Phase "C" transformers during the March 1989 solar storm.
6. The NERC Screening Criterion whitepaper does not disclose that second transformer test was conducted essentially under 20% or less load conditions, but this is disclosed in Reference 3.[49]
7. Reference 4 of the NERC Screening Criterion whitepaper is apparently a workshop presentation and is therefore unpublished.[50]

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[47] Reference 2 for the NERC Screening Criterion whitepaper is "Marti, L., Rezaei-Zare, A., Narang, A., "Simulation of Transformer Hotspot Heating due to Geomagnetically Induced Currents," IEEE Transactions on Power Delivery, vol.28, no.1, pp.320-327, Jan. 2013. On page 322 the test procedures are described:
"As another illustration, Fig. 5 shows the measured response obtained during acceptance tests on a single-phase 500/16.5-kV, 400-MVA transformer, which we will call "Transformer B." These measurements were made under no-load conditions at Fig. 4. Asymptotic values of flitch plate hotspot temperature rise versus GIC (Transformer A).Fig. 5. Measured temperature rise in Transformer B (500/16.5 kV, 400 MVA) during dc injection tests. 26 C ambient using sensors placed at several parts of the assembly, including points in the tie plate and at suspected winding hotspots. A dc current of 5 A was injected into the winding for 2 h, followed by a further step increase to 16.7 A for 1 min. The fitted function for the tie-plate hotspot is shown in Fig. 6 for a 5-A step change in current. Since measurement of the response at the 16.7-A level was terminated after just 1min, as required by the specified acceptance tests, no further fitted parameters are available for this unit. In the absence of additional asymptotic temperature information, a simplified straight-line asymptotic behavior with a slope of 15.6/5.0 C/A, has been used for the purpose of illustrating results predicted with our formulation. Unfortunately, there are nowinding hotspot measurements available for this unit."

[48] Reference 2 for the NERC Screening Criterion whitepaper helpfully discloses the reason more rigorous transformer tests under injected direct current conditions are not performed (emphasis added): Reference 2, page 325 reads:
"A more difficult issue is that most transformer manufacturers do not routinely perform dc current injection tests; some manufacturers are unable to perform the tests, and asset owners would be reluctant to carry out such tests for the current values needed to fully characterize the asymptotic temperature behavior such as the one shown in Fig. 4 *for fear of damaging the transformer*."

[49] See Lahtinen, Matti. Jarmo Elovaara. "GIC occurrences and GIC test for 400 kV system transformer". IEEE Transactions on Power Delivery, Vol. 17, No. 2. April 2002. Page 560 discloses:
"During the test, the winding temperature did not rise because the phase currents were rather low and were less than 20% of the rated ones."

Given the egregious defect of the 75 amp per phase Screening Criterion for transformer thermal impact assessments, it is helpful for the Commissioners to understand its history. Originally, the Standard Drafting Team set the Screening Criterion at 15 Amps, where it persisted at this level through Draft 1, Draft 2, Draft 3, and Draft 4 used as the basis for three separate ballots. When the standard failed on Ballot 3, the 15 amp Screening Criterion was upwardly reset by a *factor of five* to 75 amps, whereupon the standard handily passed on the next ballot.

The requirements of FERC Order 779 allowed for uniform assessment measures, not uniform measures to exempt transformers from assessment. The Commissioners should remand the 75 amp Screening Criterion for transformer thermal impact assessment.

Transformer Thermal Impact Assessments

With the average age of the extra high voltage transformers in the fleet up to 40 years old, it is not practical or reliable for utilities to perform transformer thermal impact assessments in most cases. Through the GMD Task Force, we have heard that some transformer manufacturers are providing "GIC withstand" warranties for new transformers. The Commission should remand the standard to require "GIC withstand" as a potential mitigation measure only for newly purchased transformers where the transformer manufacturer will warranty the transformer for a specified level of GIC withstand. The allowed GIC withstand amperage in a utility's transformer thermal impact assessment should never exceed the manufacturer's warranty; if the manufacturer will not provide a GIC withstand warranty, no hardware mitigation exception for transformer thermal impact assessment should be permitted under the standard.

Inadequate Protection of BPS Equipment and System Stability

In the GMD NOPR, FERC sought comment from NERC on conditions that could cause load loss due to system instability:

> 56. NERC maintains that Table 1 sets forth requirements for system steady state performance. NERC explains that Requirement R4 and Table 1 "address assessments of

[50] Reference 4 is: "J. Raith, S. Ausserhofer: "GIC Strength verification of Power Transformers in a High Voltage Laboratory", GIC Workshop, Cape Town, April 2014."

> the effects of GICs on other Bulk-Power System equipment, system operations, and system stability, including the loss of devices due to GIC impacts."
>
> Table 1 provides, in relevant part, that load loss and/or curtailment are permissible elements of the steady state:
>
> Load loss as a result of manual or automatic Load shedding (e.g. UVLS) and/or curtailment of Firm Transmission Service may be used to meet BES performance requirements during studied GMD conditions. The likelihood and magnitude of Load loss or curtailment of Firm Transmission Service should be minimized.
>
> **Discussion**
>
> 57. The Commission seeks comment from NERC regarding the provision in Table 1 that "Load loss or curtailment of Firm Transmission Service should be minimized."

FERC was right to solicit comments from NERC, because defects in the standard could cause voltage collapse, High Voltage Direct Current (HVDC) link tripping, protective device tripping, and harmonic production.

Voltage Collapse and Reactive Power Modeling

In FERC Order 779 (p. 11), the Commission recognized that voltage instability and subsequent voltage collapse is one of several GMD scenarios:

> 16. We issue this directive recognizing, as we did in the NOPR, that there is an ongoing debate as to the likely effect of GMDs on the reliable operation of the Bulk Power System. As discussed below, the NOPR comments reflect these differing views, with some comments supporting the *NERC Interim GMD Report's conclusion that the worst-case GMD scenario is "voltage instability and subsequent voltage collapse,"* while other comments endorse the Oak Ridge Study's conclusion that a severe GMD event could put Bulk-Power System transformers at risk for failure or permanent damage.

Ironically, the standard does not require modeling of reactive power consumption and potential voltage collapse. Nonetheless, some network operators have begun to model for this scenario. For example, Bonneville Power Administration (BPA) modeled their network using PowerWorld™ and we were able to obtain the results through a Freedom of Information Act request.[51]

[51] See BPA GMD Impact Assessment, TIP 264 GIC R&D," by Scott Dahman of PowerWorld Corporation for Bonneville Power Administration, September 30, 2013, filed as Resilient Societies' reference document 15 on FERC Docket No. RM15-11-000.

The BPA network model shows that voltage collapse occurs at a geoelectric field of 3.85 V/km:

BPA GMD Impact Assessment
Revised September 30, 2013

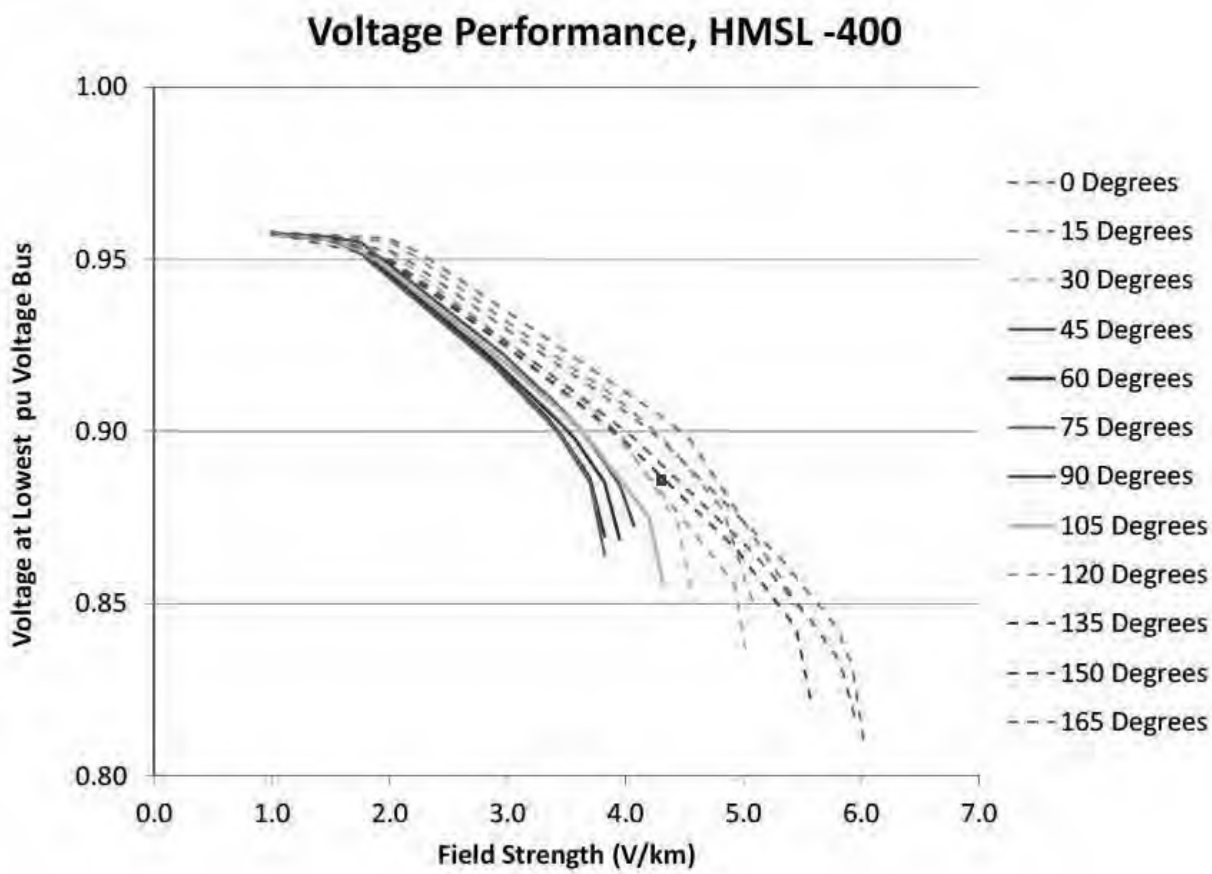
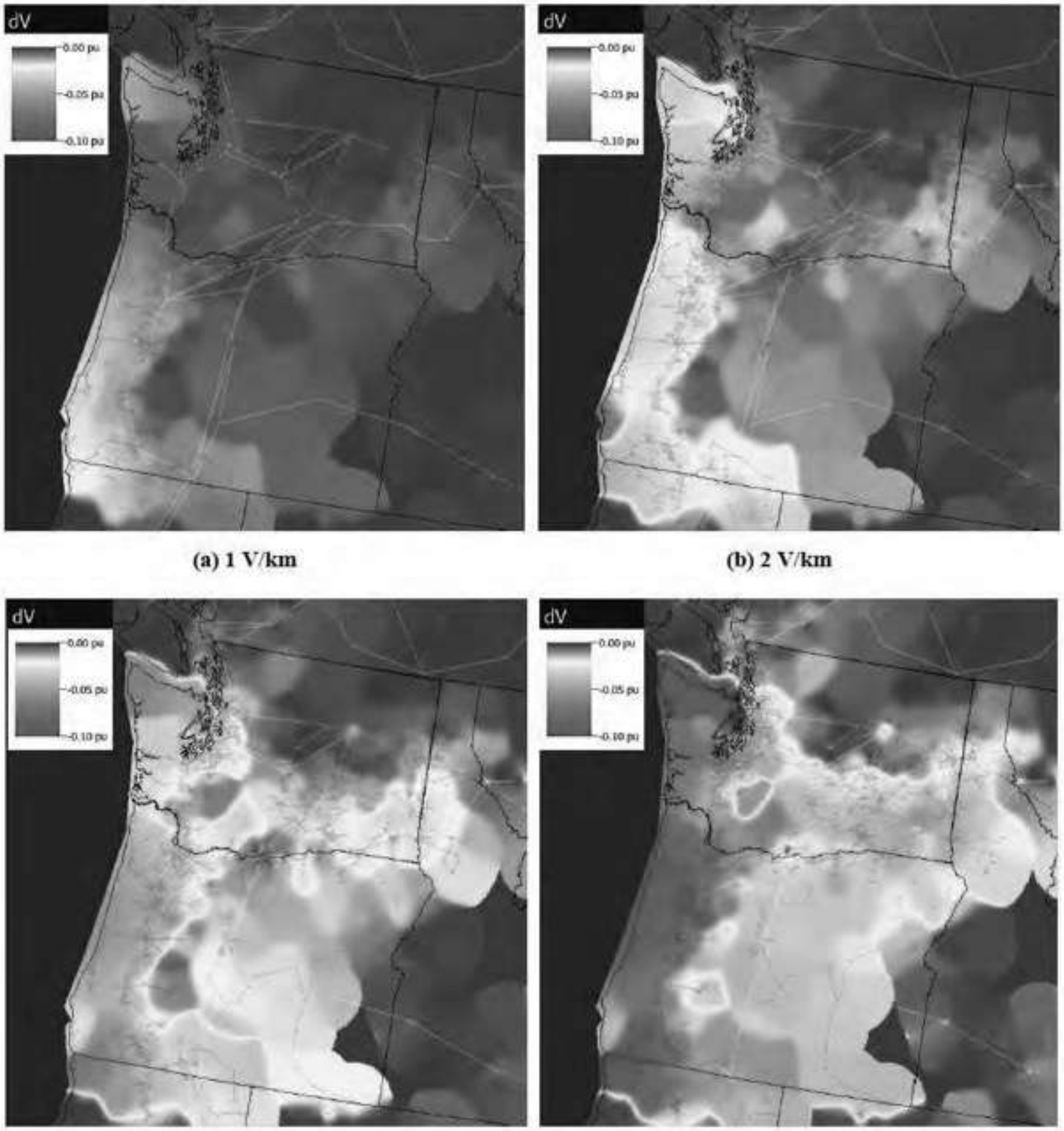


Figure 6

Figure 9: Voltage performance as a function of field strength and latitude

The BPA network is predominantly in the “PB-1 - Pacific Border (Willamette Valley)” physiographic region, with a scaling factor of 0.62 according to the NERC standard. The geomagnetic latitude of Portland, Oregon within the BPA network is 50.98 degrees, with a scaling factor of 0.35. The combined scaling factor is 0.22, resulting in a Benchmark GMD Event of 8 V/km in Quebec scaled down to 1.74 V/km at Portland. According to the BPA model, system voltage would be at approximately 95% at this field strength, within system stability limits.

However, this example also shows the importance of a technically justified Benchmark GMD Event, combined with required modeling for voltage collapse. If the Benchmark GMD Event were set at 20 V/km in Quebec, the scaled geoelectric field at Portland would be 4.36 V/km; voltage collapse would occur under the Benchmark GMD Event.



(a) 1 V/km (b) 2 V/km

(c) 3 V/km (d) 3.85 V/km - last valid solution

Figure 8 - Voltage Change Contours, HMSL -400, 75 degrees Electric Field Orientation

Figure 10: Voltage Change Contours

HVDC Tripping

Increasingly, High Voltage Direct Current (HVDC) links are transferring both power and potential outage contingencies over long distances and across the boundaries of Reliability Coordinators. Below is a table of HVDC links of capacity 250 MW and above within the United States, both operational and planned:

Major High Voltage Direct Current Ties 250MW and Above within United States								
HVDC Link	End 1	Reliability Coordinator End 1	End 2	Reliability Coordinator End 2	Total Length (km)	DC Voltage (kV)	Power (MW)	First Year of Service
Tres Amigas Superstation	Clovis, New Mexico	SPP/ERCOT/Peak	Clovis, New Mexico	SPP/ERCOT/Peak	B-to-B	765	5,000*	2016
Pacific DC Intertie	Celilo, OR	Peak Reliability	Sylmar, CA	Peak Reliability	1,362	500	3,800	1970
Plains & Eastern Clean Line	Texas County, OK	SPP	Shelby County, TN	TVA	1,207	600	3,500	2018
Rock Island Clean Line	O'Brien County, IA	MISO	Grundy County, IL	PJM	805	600	3,500	2017
TransWest Express	Rawlins, WY	Peak Reliability	Las Vegas, NV	Peak Reliability	1,167	600	3,000	2015
Intermountain Power Project	Intermountain, UT	Peak Reliability	Adelanto, CA	Peak Reliability	785	500	2,400	1986
Phase II	Radisson, QC	Hydro Quebec, TE	Ayer, MA	ISO New England	1,480	450	2,000	1991
CU (Great River Energy HVDC)	Underwood, ND	MISO	Rockford, MN	MISO	687	400	1,000	1979
Neptune Cable (Long Island)	Hicksville NY	NY ISO	Sayreville, NJ	PJM	105	500	660	2007
Hudson Tranmission Project	Bergen County, NJ	PJM	New York City	NY ISO	10	180	660	2013
Welch HVDC	Titus County, TX	ERCOT	Mount Pleasant, TX	SPP	10	170	600	1995
Square Butte	Center, ND (Young)	MISO	Adolph, MN	MISO	749	250	500	1977
Trans Bay Cable	Pittsburg, CA	Peak Reliability	San Francisco, CA	Peak Reliability	85	200	400	2010
Cross Sound Cable	New Haven, CT	ISO New England	Shoreham, NY	NY ISO	40	150	330	2002
*Tres Amigas is planned for eventual 30 GW capacity.								
Sources: IEEE, ABB, Siemens, Tres Amigas LLC, Wikipedia								

Table 5: HVDC Ties

The trend of high capacity, long distance HVDC links is accelerating as more renewable generation is transported long distances for compliance with environmental regulations.

Real-world experience has shown that HVDC links are highly vulnerable to GMD events, because harmonics affect the firing angle of commutators.[52] As the above table shows, HVDC links present large contingencies up to 5,000 MW. It is a fallacy to assume that failures of bi-pole HVDC links will occur independently at different times, allowing contingency planning for

[52] N. Mohan, V. D. Albertson, T. J. Speak, J. G. Kappenman, M. P. Bahrman, "Effects of Geomagnetically-Induced Currents on HVDC Converter Operations," N. Bahrman, IEEE PAS Transactions, Vol. PAS-101, November 1982, pp. 4413-4418.

only half of the capacity. Experience with the Phase II link running from Radisson, Quebec to Sandy Pond, Massachusetts shows that both poles can fail during the same solar storm.

The Phase II link tripped during solar storms on 03/24/91, 05/28/91, 10/27/91, and 10/28/91. According to our calculations using the Standard TPL-007-1 geomagnetic scaling factors and ground model scaling factors, all of these trips occurred during solar storms at 21% or less of the NERC Benchmark GMD Event.

The FERC Commissioners should remand Standard TPL-007-1 for lack of a mandatory requirement for protection of HVDC links against GMD.

Disruptive Harmonic Production

FERC Order 779 (p. 5) recognized disruptive harmonics that can cause sudden collapse of the Bulk Power System.

> GICs can cause "half-cycle saturation" of high-voltage Bulk-Power System transformers, which can lead to increased consumption of reactive power and creation of disruptive harmonics that can cause the sudden collapse of the Bulk-Power System.

NERC's own report GMD Interim Report in 2012 described the impacts of harmonic production, including tripping of protective devices.[53]

FERC has a legislative mandate in Section 215 of the Federal Power Act to prevent system instability, including sudden collapse. The Commission should remand Standard TPL-007-1 because it does not contain any requirement for mitigation of harmonics that can cause system instability and unanticipated failure of system elements, including HVDC links, as we have shown in this comment.

Exemptions of Networks Operating Below 200 kV

The GMD NOPR (p. 10) recited the exemption of networks with high-side voltages below 200 kV:

[53] 2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System," NERC, February 2012, available at http://www.nerc.com/files/2012GMD.pdf, last accessed on July 26, 2015.

> 13. NERC states that proposed Reliability Standard TPL-007-1 applies to planning coordinators, transmission planners, transmission owners and generation owners who own or whose planning coordinator area or transmission planning area includes a power transformer with a high side, wye-grounded winding connected at 200 kV or higher. NERC explains that the applicability criteria for qualifying transformers in the proposed Reliability Standard is the same as that for the First Stage GMD Reliability Standard in EOP-010-1, which the Commission approved in Order No. 797.

While the FERC-approved Bulk Electric System definition includes transmission at voltages at 100kV and above, and while multiple GMD impacts on Static VAR Compensators and other equipment operating between 100kV and 200kV were reported by electric utilities during the March 1989 solar storm, Standard TPL-007-1 would exempt Transmission Operators with equipment operating between 100 kV and 200 kV. Many Transmission Operators operate Static VAR Compensators, capacitors, and other equipment between 100 kV and 200 kV: equipment designed to provide reactive power and to stabilize transmission networks during GMD. Below is a listing of March 13, 1989 storm impacts on critical equipment operating at less than 200 kV, as disclosed by a FERC-sponsored study:

March 13, 1989 Geomagnetic Disturbance

Chronology of Reported North American Power Grid Events

Adapted from Pages A2-2 to A2-8 of "Geomagnetic Storms and Their Impacts on the U.S. Power Grid" Oak Ridge National Laboratory, January 2010

Event No.	Date	Time (EST) From	To	Area or System	Event	Base kV	Comments
29	3/13/1989	245		Minn. Power	Capacitor	115	Lost capacitor bank at Nashwauk. Neut overcurrent relay
44	3/13/1989	608		Cent. Hud.	Capacitor	69	Pulvers Corners capacitor trip
47	3/13/1989	615		APS	Capacitor	138	7 Capacitors tripped
54	3/13/1989	618		Va. Pwr.	Capacitor	115	Virginia Beach
57	3/13/1989	619		Cent. Hud.	Capacitor	115	Hurley Ave. capacitor trip
94	3/13/1989	1645	2000	WPL	Voltage	138	Various voltage problems. Regulators hunting
100	3/13/1989	1655		Atl. Elec.	Voltage	69	
108	3/13/1989	1658		BPA	Capacitor	115	Tripped by neutral time ground at 4 substations
175	3/13/1989	2017		NEPOOL	Capacitor	115	Orrington capacitors (1, 2, &3) opened and would not close
183	3/13/1989	2020	2030	Atl. Elec.	Voltage	138	
192	3/13/1989	2032		PJM		69	Nazareth Capacitors tripped

Table 6: Impacts on equipment operating below 200kV during 1989 GMD event

These are real-world and non-trivial GMD impacts during a moderate storm with geoelectric fields of only 2 volts/kilometers in high latitude Quebec.

We researched reactive power support equipment installed in the United States and found three sources: lists of reference accounts published by ABB and Siemens, and individual company disclosures. Notably, there was a high degree of overlap between the three sources. It appears ABB produces the vast majority of SVC/STATCOM for the United States. Based on the ABB sample, we estimate that about 25% of SVC/STATCOM units within the bulk electric system of the United States operate between 100 kV and 200 kV. Reactive power is in particularly short supply during GMD events because transformers in half-cycle saturation consume reactive power. Unexpected tripping of reactive power resources can cause both system separation and cascading system collapse. In fact, the proximate cause of the March 1989 Hydro Quebec blackout, occurring in only 93 seconds, was loss of seven SVC's, all tripping within a 59 second interval.[54]

Below is an example list of reactive power resources within the United States operating between 100 kV and 200 kV, the vast majority installed since 1989:

[54] See S. Renaud and S. Guillon, "Hydro-Québec and GIC: Power Network Studies and Simulation Developments," Presentation of HQ to the JRC Workshop, Ispra, Italy, Oct. 29, 2013, at VG 6, 16, 18 and 24 of 56. See http://ipsc.jrc.ec.europa.eu/fileadmin/repository/sta/SpaceWeatherWorkshop/Session-3_Guillon.pdf.

Examples of Reactive Power Resources 100-200 kV within United States						
Equipment	Utility	Location	Voltage (kV)	First Year of Service	Inductive Rating (MW)	Capacitive Rating (MW)
SVC	AEP	Beaver Creek	138	1978	0	0
SVC	Kansas Gas & Electric	Murray Gill, KS	138	1985	25	200
SVC	Kansas Gas & Electric	Gordon Evans, KS	138	1985	0	300
SVC	Alaska Energy Authority	Soldatna, AK	115	1991	40	70
SVC	Alaska Energy Authority	Daves Creek, AK	115	1991	10	25
SVC	Virginia Power	Colington, VA	115	1996	30	167
STATCOM	COM Central and South West Corp	Eagle Pass HVDC	138	1999	72	72
SVC	Connectiv	Nelson	138	1999	100	150
SVC	ISO Ispat	Ispat	138	1999	0	200
STATCOM	Austin Energy	Holly, USA	138	2003	80	110
SVC	Pacific Gas & Electric	Potero, CA	115	2003	100	240
SVC	Golden Valley Electric Association	Jarvis Creek	138	2004	8	45
SVC	Georgia Power Co	Noth Dublin, GA	115	2005	unknown	unknown
SVC	Duke Power	Beckerdite	100	2006	100	300
SVC	Tucson Electric Power	Tucson, AZ	138	2006	75	200
SVC	Dominion Power	Colington, VA	115	2007	0	0
SVC	Nstar	Barnstable, MA	115	2008	113	225
SVC	Oncor	Renner 1	138	2008	265	300
SVC	Oncor	Parkdale 1	138	2008	265	300
SVC	Oncor	Parkdale 2	138	2008	265	300
SVC	Oncor	Renner 2	138	2009	265	300
SVC	AEP	Hamilton 1	138	2011	25	100
SVC	AEP	Hamilton 2	138	2011	25	100
SVC	Pepco (PHI)	Nelson	135	2011	0	0
SVC	Rochester Gas & Electric	Station 124, NY	115	2011	100	200
SVC	Pepco (PHI)	Ocean City, MD	138	2012	75	75
SVC	Entergy	Porter, TX	138	unknown	unknown	unknown
STATCOM	San Diego G&E	Talega, CA	138	unknown	unknown	unknown
STATCOM	Vermont Electric	Burlington, VT	115	unknown	unknown	unknown
Source: ABB, Siemens, Company Disclosures						

Table 7: List of Reactive Power Resources, 100-200 kV, in United States

In 2013 BPA commissioned a PowerWorld study of vulnerability of its network to GMD.[55] Interestingly, the study concluded that coastal 115 kV networks are especially susceptible to voltage drop.

> **Uniform Field Analysis Conclusions**
>
> The uniform field analysis reveals some vulnerability of the Pacific Northwest power grid due to GIC transformer reactive power losses. *The Olympic peninsula and coastal 115 kV networks are especially susceptible to voltage drop.* The HMSL +550 scenario performs slightly better than the HMSL -400 scenario, likely a result of it having more spinning generator reactive power reserves. GMD electric field orientations of 60-90 degrees pose the greatest threat in both scenarios. The next phase of analysis will examine methods to increase the ability of the network to withstand GMD events.

The arbitrary exemption of networks operating between 100 kV and 200 kV, without any specific study by owners and operators, is technically unreasonable, discriminatory, preferential, and inconsistent with real-world scientific evidence. Critical equipment can operate between these voltages, as the examples for SVCs, STATCOMs, and HVDC links show. Modeling within the BPA system shows that 115 kV networks are vulnerable to GMD. The Commission should remand to eliminate the exemption for networks operating between 100 kV and 200 kV.

Safety Factors and Multiplicative Impacts of Defective Assumptions

FERC Order 779 (p. 43) recited the position of the Electric Infrastructure Security (EIS) Council on safety factors:

> "EIS states that, because the science of GMDs is inexact, an event twice as large as the largest expected GMD should be used as a safety margin."

The Commission was right to recite this comment, because safety factors are commonly used in a variety of engineered structures and products. For example, a safety factor of 2 is commonly used in built structures. Automobiles commonly have a safety factor of 3.[56]

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[55] See "BPA GMD Impact Assessment, TIP 264 GIC R&D," by Scott Dahman of PowerWorld Corporation for Bonneville Power Administration, September 30, 2013, filed as Resilient Societies' reference document 15 on FERC Docket No. RM15-11-000.

[56] See "Factor of Safety," Wikipedia, available at https://en.wikipedia.org/wiki/Factor_of_safety, last accessed 7/25/2015.

However, the “Implicit Safety Margin” in Standard TPL-007-1 is only 1.4 (8 V/km over 5.77 V/km.)

The Commission should recognize that several of the potential defects in Standard TPL-007-1 have multiplicative impact—in other words, biases in the NERC Benchmark GMD Event and transformer thermal Screening Criterion multiply among themselves, producing a level of required protection that may be many times below a prudent and technically justified level.

In the below table, we show a “NERC Scenario” consistent with Standard TPL-007-1 and other reasonable scenarios designated “Middle” and “Conservative,” along with the multiplicative impact of alternative assumptions. Notably, key elements of the other reasonable scenarios are based on preliminary results by scientists on the NERC GMD Task Force or, alternatively, were part of draft versions of Standard TPL-007-1. For example, the GMD Task Force proposed 1-in-100 Year Reference Storm peak geoelectric fields of 20 V/km and 40 V/km in July and February 2013, respectively. As another example, a threshold of 15 amps for the transformer thermal Screening Criterion was embedded in Standard TPL-007-1 for Drafts, 1, 2, 3, and 4.

Multiplicative Impacts of Geomagnetic Disturbance Scenario Assumptions			
NERC Standard vs. Other Reasonable Scenarios at Specific Locations			
Values from References	Scenario		
	NERC Standard	Middle	Conservative
Benchmark GMD Event			
1-in-100 Year Reference Storm	5.77 V/km	20 V/km	40 V/km
NERC "Implicit Safety Margin"	1.4	n/a	n/a
1-in-100 Year Reference Storm with "Safety Margin"	8 V/km	20 V/km	40 V/km
Geomagnetic Latitude Scaling Factor within U.S.	0.1 to 0.5	0.30	0.50
Ground Model Scaling Factor within U.S.	0.22 to 1.17	0.70	1.17
Transformer Assessment			
Thermal Impact Screening Criterion	75 Amps	45 Amps	15 Amps
Multiplicative Impact Ratios	Scenario		
(Ratios: Middle & Conservative to NERC Standard)	NERC Standard	Middle	Conservative
Benchmark GMD Event			
1-in-100 Year Reference Storm (V/km)	1.0	2.5	5.0
Geomagnetic Latitude Scaling within U.S.	1.0	3.0	5.0
Ground Model Scaling Factor within U.S.	1.0	3.2	5.3
Multiplicative Product for Benchmark GMD Event	1.0	23.9	133.0
Transformer Thermal Assessment			
Thermal Impact Screening Criterion (amps)	1.0	3.0	5.0
Overall Safety Factor	1.0	2.0	3.0
Total Multiplicative Products for All Assumptions	1	143	2,000
Notes:			
1. "Middle" and "Conservative" 1-in-100 Year Reference Storm scenarios from work of NERC GMD Task Force.			
2. "Middle" Geomagnetic Scaling Factor is midpoint of NERC Standard's range within U.S. latitudes.			
3. "Conservative" Geomagnetic Scaling Factor is high-point of NERC Standard's range within U.S. latitudes.			
4. "Middle" Ground Model Scaling Factor is midpoint of NERC Standard's range within U.S. latitudes.			
5. "Conservative" Ground Model Scaling Factor is high-point of NERC Standard's range within U.S. latitudes.			
6. "Middle" Thermal Impact Screening Criterion is midpoint of 75 and 15 amps.			
7. "Conservative" Thermal Impact Screening Criterion at 15 amps is NERC Standard value for Ballots 1 and 2.			
8. "Middle" Safety Factor is standard value for built structures.			
9. "Conservative" Safety Factor is standard value for automobiles.			

Table 8: Multiplicative Impacts of GMD Scenario Assumptions

We urge the Commission to understand that fixing just one factor in Standard TPL-007-1, such as the 1-in-100 Year Reference Storm, will not fix all the other defective standards. Importantly, because the various component factors are multiplicative, the overall impact of hazard-reducing sub-models is to drastically reduce the prudence and the realism of the resulting Benchmark GMD Event design and benchmark standard.

We further urge the Commission to add a requirement that utilities annually disclose the number of extra high voltage transformers in their fleet, the number undergoing thermal assessment, the number of transformers determined to need mitigative measures, and the number and categories of mitigative measures among hardware protection, spare units, isolation from service, or other mitigative strategy. If the disclosed number of transformers needing thermal assessment and/or the number of transformers with installed hardware protection or other mitigative measures is trivial, then the Commission will know that the intent of FERC Order 779 for hardware protection is being evaded.

Responses to FERC Solicitation of Comments

GIC Monitoring Devices

GMD NOPR, p. 28:

> 46. The Commission proposes to direct NERC to develop revisions to Reliability Standard TPL-007-1 requiring installation of monitoring equipment (i.e., GIC monitors and magnetometers) to the extent there are any gaps in existing GIC monitoring and magnetometer networks, which will ensure a more complete set of data for planning and operational needs. Alternatively, we seek comment on whether NERC itself should be responsible for installation of any additional, necessary magnetometers while affected entities would be responsible for installation of additional, necessary GIC monitors. As part of NERC's work plan, we propose to direct that NERC identify the number and location of current GIC monitors and magnetometers in the United States to assess whether there are any gaps.

GMD NOPR, p. 29:

> 47. NERC maintains that the installation of monitoring devices could be part of a mitigation strategy. We agree with NERC regarding the importance of GIC and magnetometer data. As the Commission stated in Order No. 779, the tools for assessing GMD vulnerabilities are not fully mature. Data from monitors are needed to validate the

> analyses underlying NERC's proposed Reliability Standard and the analyses to be performed by affected entities.

NOPR, p. 30:

> 48. Accordingly, rather than wait to install necessary monitoring devices as part of a corrective action plan, GIC and magnetometer data should be collected by applicable entities at the outset to validate and improve system models and GIC system models, as well as improve situational awareness. To be clear, we are not proposing that every transformer would need its own GIC monitor or that every entity would need its own magnetometer. Instead, we are proposing the installation and collection of data from GIC monitors and magnetometers in enough locations to provide adequate analytical validation and situational awareness. We propose that NERC's work plan use this criterion in assessing the need and locations for GIC monitors and magnetometers.

Geomagnetically-Induced Current (GIC) monitors are commercially available and can be purchased for as little as $10,000 to $15,000 each.[57] Nonetheless, Standard TPL-007-1 has no requirement for GIC monitoring or mandatory sharing of GIC data for scientific study. We agree with the Commission that Standard TPL-007-1 should be remanded for mandatory installation of GIC monitors and magnetometers. Moreover, data from these GIC monitors and magnetometers should be made available to the public to better scientific understanding of GMD effects on the electric grid.

Public Dissemination of GIC Data

In the GMD NOPR (p. 24), the Commission sought comment on barriers to public dissemination of GIC and magnetometer readings:

> The Commission seeks comment on the barriers, if any, to public dissemination of GIC and magnetometer readings, including if the dissemination of such data poses a security risk and if any such data should be treated as Critical Energy Infrastructure Information or otherwise restricted to authorized users.

Resilient Societies supports making GMD data (e.g., GIC monitoring and magnetometer data) available to researchers for study and for publication, peer review, and professional workshop

[57] See Resilient Societies Findings and Recommendations to the Maine Public Utilities Commission in Maine PUC Docket 2013-00415, October 15, 2013 and December 18, 2013. Costs of commercially available GIC monitoring and automated remote readout have declined from $200,000 per unit to $10,000 to $15,000 per monitoring unit over the past two years. See http://resilientsocieties.org/docketfilings.html, last accessed March 23, 2014.

critique. The Commission should order applicable entities to establish regular procedures for public dissemination of GIC and magnetometer readings. Without disclosure and dissemination of GIC and magnetometer readings, FERC will be enabling an industry-controlled machinery—the NERC reliability-standard-setting process—to generate and perpetuate liability protections without strong technical basis. Concurrently, FERC will aid and abet the protection of electric utility investors while shifting economic losses and societal disruptions from prolonged blackout caused by GMD to all other groups in our society.

The risk of blackout from GMD has been well known since the Hydro Quebec outage in March 1989. However, GIC data has been held as confidential and proprietary by the EPRI SUNBURST consortium and also by individual utilities. This practice has greatly impeded independent scientific study of GMD effects and caused inadequate technical understanding. Non-disclosure of GIC data and GMD impacts further impeded the setting of a technically justified Benchmark GMD Event, a Screening Criterion for transformer thermal assessment, and other necessary requirements and measures in the standard.

There is no security risk to releasing GIC and magnetometer readings. These are indicators of naturally occurring phenomena and their non-disclosure will have absolutely no preventative effect on whether GMD disasters occur or not. Already, GIC data is made available in real time by BPA on their website. TVA has released GIC data under the Freedom of Information Act. On a selected basis, individual private utilities have also released GIC data at the GMD Task Force and other venues. Utilities have disclosed the locations of over 100 GIC monitoring sites.

In order for GIC data to be relevant and actionable for scientific study, it must necessarily include the location of the monitor. Some monitors are located at critical substations and some are located at non-critical substations. As the number of monitors increases and ultimately will number several hundred, the colocation of a GIC monitor will be a very poor indicator of whether a substation is critical or not. Already, there are over 100 GIC monitors installed. Moreover, the location of electric grid substations is not protected information—substation locations are freely available via commercially available databases, including the ubiquitous Google Earth online mapping service.

FERC Order No. 683 clarified the definition of Critical Energy Infrastructure Information (CEII) (pp. 4-5):

> CEII is clarified as specific engineering, vulnerability, or detailed design information about proposed or existing critical infrastructure that: (1) relates details about the production, generation, transportation, transmission, or distribution of energy; (2) could be useful to a person in planning an attack on critical infrastructure; (3) is exempt from mandatory disclosure under the Freedom of Information Act, 5 U.S.C. 552 (2000); and (4) does not simply give the general location of the critical infrastructure. The particular clarifications consist of adding the words "specific engineering, vulnerability, or detailed design" at the Docket No. RM06- 24-000 - 5 - beginning of § 388.113(c)(1) and adding the words "details about" at the beginning of § 388.113(c)(1)(i).
>
> 7. The Commission further clarifies that narratives such as the descriptions of facilities and processes are generally not CEII unless they describe specific engineering and design details of critical infrastructure.

In order for GIC and magnetometer readings to be considered CEII, they must meet all four conditions specified in FERC Order 683. These readings fail on all four conditions:

1. GIC and atmospheric magnetic fields are not usable "energy."
2. GIC and magnetometer readings would not be useful to persons planning a terrorist attack, because that person could not use real-time or delayed readings to predict GMD events in the future. In fact, public forecasts by the NOAA Space Weather Prediction Center would have more utility for terrorists, but because these forecasts are not restricted as CEII, neither should real-time readings be restricted for security reasons.
3. By releasing GIC readings under the Freedom of Information Act multiple times, the U.S. Government has established that this information is not exempt from mandatory disclosure.
4. Any locational data with GIC and magnetometer readings could simply give the location of the monitor, i.e., latitude and longitude, and need not give any other information about critical infrastructure. FERC Order 683 specifically states that general location is not CEII.

Lastly, it would be unprecedented for a federal agency to restrict public use of information on naturally occurring hazards. There would be public outrage if readings on earthquakes, floods, hurricanes, and the like were restricted and there will be similar outrage if information on solar storm hazards is concealed from the public. Restriction of public dissemination of GIC and magnetometer readings may be in the interest of electric utilities seeking to avoid the installation of hardware protective devices, but it is not in the public interest.

Lowest Common Denominator Standard

FERC Order 672[58] established that a mandatory Reliability Standard should not reflect "the lowest common denominator," and should have no undue effect on competition. Moreover, the Commission established that it will not defer to the ERO with respect to a Reliability Standard's effect on competition. The Commission rejected the notion that an ANSI-certified process automatically satisfies the statutory standard of review for discriminatory impact or negative effect on competition. The relevant paragraphs from Order 672 are quoted below:

> 29. A mandatory Reliability Standard should not reflect the "lowest common denominator" in order to achieve a consensus among participants in the ERO's Reliability Standard development process. Thus, the Commission will carefully review each Reliability Standard submitted and, where appropriate, *remand an inadequate Reliability Standard to ensure that it protects reliability, has no undue adverse effect on competition*, and can be enforced in a clear and even-handed manner. Further, the Final Rule allows the Commission to set a deadline for the ERO to submit a proposed Reliability Standard to the Commission to ensure that the ERO will revise in a timely manner a proposed Reliability Standard that is not acceptable to the Commission. These provisions, as well, will strengthen the ERO and Regional Entities by providing mechanisms to achieve effective and fair Reliability Standards.
>
> 40. The Commission may approve a proposed Reliability Standard (or modification to a Reliability Standard) if it determines that it is just, reasonable, not unduly discriminatory or preferential, and in the public interest. In its review, the Commission will give due weight to the technical expertise of the ERO or a Regional Entity organized on an Interconnection-wide basis with respect to a proposed Reliability Standard to be applicable within that Interconnection. *However, the Commission will not defer to the ERO or a Regional Entity with respect to a Reliability Standard's effect on competition.*

[58] FERC Statutes and Regulations, Rules Concerning Certification of the Electric Reliability Organization; and Procedures for the Establishment, Approval, and Enforcement of Electric Reliability Standards, Order No. 672, February 17, 2006, Docket No. RM05-30-000.

> 332. *As directed by Section 215 of the FPA, the Commission itself will give special attention to the effect of a proposed Reliability Standard on competition.* The ERO should attempt to develop a proposed Reliability Standard that has no undue negative effect on competition. Among other possible considerations, a proposed Reliability Standard should not unreasonably restrict available transmission capability on the Bulk-Power System.
>
> 338. We reject the notion that we should presume that a proposed Reliability Standard developed through an ANSI-certified process automatically satisfies the statutory standard of review. In this regard, *we agree with EEI and others that the development of a Reliability Standard through the ERO's stakeholder process is no guarantee that a proposed Reliability Standard does not have a discriminatory impact or negative effect on competition* even if the proposal meets its technical or operational objective beyond any restriction necessary for reliability and should not limit use of the Bulk-Power System in an unduly preferential manner. It should not create an undue advantage for one competitor over another.
>
> (Italics added.)

Standard TPL-007-1 is a "lowest common denominator" that allows a protection level below the true threat or "technically justified" Benchmark GMD Event. Competitors that contemplate "best practices" above the deficient Benchmark GMD Event may not achieve cost-recovery and will be competitively disadvantaged, therefore establishing an undue effect on competition. The reality is that the "floor" of minimal reliability standards when combined with the promise of liability protection drives out "best practices" in the marketplace for reliability.[59]

The Commission Lacks Authority to Grant Liability Shielding

In FERC Order No. 779, para. 84, the Commission addressed the fears of some industry commentators that the FERC-regulated utilities might be subject to "strict liability" for "failure

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[59] On July 21, 2015 at the Electric Infrastructure Security Council Summit VI, FERC Commissioner LaFleur indicated that the minimal standards for "electric reliability" should not preclude both the adoption of "best practices" and eligibility for cost recovery for providing protections above the minimal level required by reliability standards.
To the contrary, at the state level we have witnessed both Public Utility Commission staff in Maine and state legislators question why protective devices should be allowed if they exceed minimal NERC-FERC standards. Moreover, we have witnessed Central Maine Power identify appropriate protective equipment (such as 8 neutral blocking devices), then decline to budget for such equipment upon balloting of the proposed NERC-FERC standard. Further, NextEra Energy subsidiaries at both Point Beach, Wisconsin and Seabrook, New Hampshire have opted not to provide hardware protection for large transformers at high-vulnerability locations: for both the recently installed Point Beach GSU transformer and the soon-to-be installed Seabrook GSU transformer.

to ensure the reliable operation of the Bulk-Power System in the face of a GMD event of unforeseen severity…."

The Commission observes in FERC Order 779 (p. 55):

> 84. The Second Stage GMD Reliability Standards should not impose "strict liability" on responsible entities for failure to ensure the reliable operation of the Bulk-Power System in the face of a GMD event of unforeseen severity, as some commenters fear. The NOPR proposed to require owners and operators to develop and implement a plan so that instability, uncontrolled separation, or cascading failures of the Bulk-Power System, caused by damage to critical or vulnerable Bulk-Power System equipment, or otherwise, will not occur as a result of a GMD. While this language is taken directly from the definition of "reliable operation" in FPA section 215(a)(4), and similar language is found in the Requirements of other Reliability Standards, we clarify that owners and operators should be required to develop and implement a plan to protect against instability, uncontrolled separation, or cascading failures of the Bulk-Power System, caused by damage to critical or vulnerable Bulk-Power System equipment, or otherwise, as a result of a benchmark GMD event. The goal of the NERC standards development process should be to propose Reliability Standards that ensure the reliable operation of the Bulk-Power System in response to identified benchmark GMD events.

FERC Order 779, Para. 85 continues:

> "… Identifying robust and technically justified benchmark GMD events in the Reliability Standards, that the Bulk-Power System is required to withstand (i.e., continue "reliable operation"), addresses the concern that responsible entities might otherwise be required to prevent instability, uncontrolled separation, or cascading failures of the Bulk-Power System when confronted with GMD events of unforeseen severity. In addition, the Reliability Standards should include Requirements whose goal is to prevent instability, uncontrolled separation, or cascading failures of the Bulk-Power System when confronted with a benchmark GMD event. *Given that the scientific understanding of GMDs is still evolving, we recognize that Reliability Standards cannot be expected to protect against all GMD-induced outages.* (Emphasis added.)

Resilient Societies is troubled by FERC's delegation to NERC for selection of the Benchmark GMD Event, combined with the potential for liability relief if that solar storm intensity or duration is exceeded. Resilient Societies agrees that strict liability may not be imposed by courts of competent jurisdiction for unforeseen events. However, multiple blackouts due to GMD events have already occurred, both in North American and Europe, so utilities should be liable for failure to cost-effectively protect against severe GMD. We do not ask for strict liability, but we ask the Commission to clarify its expectation that the FERC jurisdictional entities will be held to account, and be subject to liability in the event of gross negligence or willful misconduct in planning for and mitigating solar geomagnetic storms.

It is troubling that NERC has selected a Benchmark GMD Event that appears to be a roughly one in 20 year or 1 in 25 year moderate level solar storm rather than the 1-in-100 year solar storm that NERC claims to have modeled. Various filings by John Kappenman, a recognized expert in solar storm phenomena, assert that the intensity of the so-called 1 in 100 GMD event in the NERC benchmark model has been exceeded in intensity by several lower intensity GMD events in the past forty years.

The GMD Benchmark Event is apparently designed to exclude the most severe solar storms that would cause prolonged blackouts. What will the Commission do to hold electric utilities financially responsible for potential manipulation of the Benchmark GMD Event? We ask the Commission to recognize that the primary purpose of the Reliability Standard functions of the Commission, established in the aftermath of the U.S.-Canadian Blackout of 2003, was to enhance bulk power system reliability and reduce the likelihood and consequences of large-scale electric blackouts.

The traditional view of the authority of the Commission preceding the Energy Policy Act of 2005 was that the Commission lacked legal authority to grant immunity from liability by setting reliability standards. “Prior to unbundling, retail tariffs were primarily a matter for state regulation, and most states had approved tariff provisions permitting utilities to limit their liability for service interruptions to instances of gross negligence or willful misconduct.”[60]

Hence FERC acted as if it “lacks authority to approve liability limitations in RTO [Regional Transmission Organization] tariffs.”[61]

It is within the power of the U.S. Congress to set limits on liability by statute. We assert that it would be beyond the power of the Commission to grant a liability shield for the failure, by gross

[60] Quoting Transmission Access Policy Study Group, 225 F.3d 667 at 727-728 (D.C. Cir. 2000).
[61] Ibid., at pp. 728-729.

negligence or willful misconduct, for electric utilities to invest in cost-effective measures to protect the bulk power system from geomagnetic storms that have geoelectric fields in excess of the NERC Benchmark GMD Event, or more extensive duration, or that involve the entirely foreseeable "cannibalizing" or overtaking of one solar storm by another.[62]

We ask the Commission to recognize that arbitrary liability limits above a GMD Benchmark Event, a Screening Criterion for transformer thermal impact, and other exemption avenues may be unsupported by independent scientific investigation. Unwarranted "escape hatches" in the standard that were not developed in conformity with the normal scientific methods cause economic externalities and market failures to invest in greater electric grid reliability.

To offer blanket liability limits does not align with market incentives to prevent harm if liability and accountability persist. In the realm of cybersecurity, there is an important distinction between liability shielding for voluntary reporting of cyber attacks and liability protection for underlying malfeasance in preventing cyber attacks.

As former U.S. Senator Jay Rockefeller observed in a letter on general liability protection for cyber security failures, liability protection "would turn existing market incentives for implementing best practices on their head."[63]

In the market for cyber protection and cyber insurance, the existence of cyber damage liability provides market opportunities for cyber insurance. Thus, the cyber insurance industry has incentives to assist insureds in adopting best practices, and in awarding insurance premium discounts to those entities that adopt best practices. [64]

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[62] FERC has refrained from extending liability protections in Orders No. 693 and No. 890. See also the consideration of liability exclusions, but their ultimate rejection following the "Policy Statement on Matters Related to Bulk Power System Reliability," 69 FR 22502 at 22507 (April 26, 2004).

[63] Letter from Senator Jay Rockefeller, June 3, 2013, cited by U.S. Department of Commerce.

[64] In a recent July 2015 report by Lloyds, the Business Blackout Report, provided as Reference Document No. 12 in Resilient Societies' filing in Docket RM15-11-000, the financial consequences of an extended power outage may exceed $1 trillion dollars for a 30 day blackout in the United States. A solar geomagnetic storm can have comparable economic damage and loss of life. See ongoing economic modeling by Jon D. Bate, a Resilient Societies' Intern in Appendix 1.

Some have proposed that the Commission limit the liability of Regional Transmission Organizations.[65] We strongly disagree. In particular, Resilient Societies finds it particularly troubling that the PJM Interconnection, Inc. (an RTO with sophisticated market mechanisms and planning capabilities) has, via its participation in the NERC Standard Drafting Team, promoted a Benchmark GMD Event and Screening Criterion for transformer thermal assessment that exempts consideration of hardware protection for transformers at nuclear power plants that have already failed during GMD events far smaller than the benchmark event. Of particular concern are nuclear power plants built upon the artificial island adjacent to coastal waters of Delaware Bay: Salem-1, Salem-2, and Hope Creek; and the nuclear power plants at Limerick (1 and 2) that experience saline boundary conditions during high tides, and that have apparently required down-rating of power generation during solar GMD events.[66]

If the NERC Benchmark GMD Event and Screening Criterion for transformer thermal assessment are suspect, or unscientific, or anti-scientific, at least the continuation of liability exposure can be a counterforce for prudence over the long run.

Were the Commission to assert that it has authority, without a future Act of Congress, to grant liability shielding for foreseeable harm from GMD events above the NERC GMD Benchmark Event, Resilient Societies would oppose such Commission action. We would claim that the Commission would be assuming *ultra* vires authority, and in the process placing the security of critical infrastructures at risk.

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[65] See e.g., Pierce, "Regional Transmission Organizations: Federal Limitations Needed for Tort Liability," 23 Energy L. J. 63-80 (2002).

[66] In a presentation at a GMD Workshop at Idaho National Laboratory on April 7-8, 2015, the Chairman of the Standard Drafting Team of NERC, Mr. Frank Koza, presented an ordered list of extra high voltage transformers that would require hardware protection assessment (2 EHV transformers in the AEP system above 75 amps per phase); and a ranked list of others that do not require assessment. Exempted from these dubious screening criteria for transformer thermal assessment are the transformers at the PSEG Salem nuclear plants that have already failed during solar storms. The Koza presentation on April 8, 2015 is included in Resilient Societies' Reference Documents as Ref Doc. No. 4 in this Docket.

Economic Externalities in Solar Storm Protective Measures

A 2012 study by the North American Electric Reliability Corporation (NERC) hypothesized that the most likely severe GMD scenario would be system collapse due to voltage instability, with restoration times "a matter of hours to days," if replacement transformers were readily available or unnecessary in most cases.[67] An alternative report commissioned by Oak Ridge National Laboratory and sponsored by the U.S. Department of Energy, U.S. Department of Homeland Security, and Federal Energy Regulatory Commission concluded the most likely scenario is long-term outage due to extra high voltage transformer damage, with outage periods of months to years.

Since private utility companies do not bear the full risk-adjusted societal cost of an outage, but only their own risk-adjusted costs, utilities have lower economic incentive to protect against GMD events—absent subsidy in the form of cost recovery for protective devices, strict regulatory standards, and/or legal liability via negligence claims. In contrast, society as a whole has significant economic incentive to protect against even short-term blackouts of "hours or days."

Protecting the bulk power grid against a severe GMD event creates a positive externality that benefits our electricity-dependent society in the form of avoided power outage costs. Since private utilities do not currently have sufficient incentive to invest in the socially optimal level of grid protection, the gap in protection requires government action in the form of subsidy (cost recovery for protective equipment), regulation, and/or establishment of legal liability for negligence. For more details, including summary results of an economic model confirming these conclusions, please see the draft paper, "Preliminary Economic Analysis of Electric Grid Protection Against Geomagnetic Disturbance (GMD) Events" in Appendix 1 of this comment.

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[67] 2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System," NERC, February 2012, available at https://www.frcc.com/Public%20Awareness/Lists/Announcements/Attachments/105/GMD%20Interim%20Report.pdf, last accessed on July 27, 2015.

Unperformed "Initial Actions" Assessments

In FERC Order 779, the Commission ordered "Initial Actions" assessments to be performed by NERC, at NERC's own suggestion. These assessments are to be completed by the effective date of the standard. To the best of our knowledge, none of these assessments has been initiated at this late date. We encourage the Commission to remind NERC of its obligations under FERC Order 779 (p. 36):

> **<u>Commission Determination</u>**
>
> 51. The Commission accepts the proposal in NERC's May 21, 2012 post-Technical Conference comments and directs NERC to "identify facilities most at-risk from severe geomagnetic disturbance" and "conduct wide-area geomagnetic disturbance vulnerability assessment" as well as give special attention to those Bulk-Power System facilities that provide service to critical and priority loads. As noted in NERC's comments, owners and operators of the Bulk-Power System, as opposed to NERC, will perform the assessments and special attention will be given to evaluating critical transformers (e.g., step-up transformers at large generating facilities).82 We agree with the Trade Associations that system-wide assessments could be conducted by planning authorities, or another functional entity with a wide-area perspective, in coordination with owners and operators of the Bulk-Power System. 83 NERC should oversee these efforts and provide responsible entities with a methodology for identifying "at-risk" Bulk-Power System components and "critical and priority loads" that need to be analyzed in the "Initial Actions.

FERC Order 779, p. 37:

> 52. Some commenters state that tools do not exist for conducting the "Initial Actions" assessments. As a result, the commenters assert that the schedule for completing the "Initial Actions" assessments is unrealistic because the commenters believe that the NOPR proposed to require the completion of such assessments by the filing date or implementation date of the First Stage GMD Reliability Standards. We clarify that the "Initial Actions" assessments do no need to be completed by the filing date or implementation date of the First Stage GMD Reliability Standards. The NOPR only proposed that the "Initial Actions" assessments should begin immediately (i.e., simultaneous with the development of the First Stage GMD Reliability Standards). Thus, the "Initial Actions" assessments provide a head start for analyzing the most at-risk and critical facilities before the Second Stage GMD Reliability Standards become effective and could be used to assist in performing the GMD vulnerability assessments required in the Second Stage GMD Reliability Standards. Further, to the extent that owners and operators of the Bulk-Power System have already begun to identify facilities most at-risk

from severe GMD events, those assessments should help to inform the "Initial Actions" assessments required by this final rule.

FERC Order 779, p. 38:

> 53. In NERC's May 21, 2012 post Technical Conference comments, NERC stated that all of its proposed "Initial Actions" would take 18-24 months to complete.84 The June 2012 GMD Task Force Phase 2 Scope and Project Plan estimated that "improve[d] tools for industry planners to develop GMD mitigation strategies" would be completed within 12-36 months, depending on the task, and "improve[d] tools for system operators to manage GMD impacts" would be completed within 12-24 months. Adjusting the deadline for submission of the Second Stage GMD Reliability Standards to 18 months allows time to identify facilities most at-risk from severe geomagnetic disturbance and to conduct wide-area geomagnetic disturbance vulnerability assessment, with special attention being given to those Bulk-Power System facilities that provide service to critical and priority loads, before the effective date of the Second Stage GMD Reliability Standards.

Lack of Due Process in NERC Standard-Setting

Oak Ridge National Laboratory estimates that a severe solar storm would interrupt power to as many as 130 million Americans. Accordingly, a reliability standard to prevent a blackout from GMD should deserve the highest level of procedural attention from NERC staff and its independent trustees.

The Foundation for Resilient Societies diligently objected to the TPL-007-1 in the NERC standard-setting process, bringing forth a Level 1 Appeal to NERC staff and a Level 2 Appeal to a subcommittee of the NERC Board of Trustees. The independent trustees of NERC should have a fiduciary duty to hear Level 2 Appeals on a timely basis and render decisions in time for the public to comment in federal rulemaking. However, as of the date we submit our comments on this docket, we have yet to learn of the disposition of our appeal, nor will we or other commentators have a citable record of our Level 2 Appeal. This is a gross violation of due process that has caused us irreparable harm in the preparation of our comments and in the federal rulemaking process.

Summary of Rationale for Remand

NERC was once a voluntary standard-setting organization, but as designated Electric Reliability Organization, it has a duty to propose standards that are technically justified. Unfortunately, with Standard TPL-007-1, NERC has failed in its duty to the Commission and to the public. Both NERC and FERC will defeat the purpose of the Energy Policy Act of 2005 if they combine a standard with barriers to hardware protection against GMD, and liability protection against negligence that diminishes a robust marketplace for higher reliability of electric service.

The substantive facts illuminated in this comment show that Standard TPL-007-1 is defectively drafted and will not protect the safety of the public, except by voluntary action outside of the requirements of the standard.

Importantly, implementation of “best practices” above minimums set in the standard may not be eligible for cost recovery and therefore are likely to be put aside. Further, by proposing liability protection in FERC Order No. 779, FERC is effectively disabling prudent underwriting by the insurance and reinsurance industries and implementation of “best practices.” Instead of inspecting utility operators and rewarding through reduced insurance premiums “best practices,” insurers may watch from the sidelines, constrict the scope of their underwriting, or both.

Reliability Standard TPL-007-1 is a “paper compliance” standard that establishes a Benchmark GMD Event so low, and a transformer thermal assessment Screening Criterion so high, that essentially no hardware protection will be required for nearly all power transformers exposed to GMD impacts. In return for GMD Vulnerability Assessments that will determine in most cases that no tangible action is necessary, electric utilities would claim to receive liability protection for following a federally approved reliability standard.[68]

We ask the Commission to reject this fundamentally flawed and imprudent framework for Standard TPL-007-1 that has allowed NERC and the electric utility industry to pile imprudent

[68] Resilient Societies challenges any FERC claim of authority to grant liability protection by issuance of one or more reliability standards.

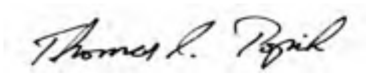
assumption on top of imprudent assumption. The result is a miasma of exemptions and inaction. The Commission should remand the entire standard TPL-007-1 to NERC for fundamental reassessment and improvements.

We also urge the Commission to seek assistance from all sources of expertise, including the Department of Defense (DOD) Defense Threat Reduction Agency (DTRA) and from the U.S. Department of Energy (DOE) National Laboratories, with the support of DOE on issues including: vibration effects (Idaho National Laboratory [INL] and DoD DTRA); interactions between installation of E1 and E2 protective hardware upon vulnerability to E3 (INL and DTRA); installation of E3 protective hardware upon E1 reduced vulnerability and mitigation cost impacts (INL and DTRA); coastal effects modeling ; GMD modeling (Los Alamos National Laboratory); and magnetotelluric modeling (USGS).

A better framework would be to require utilities to protect up to a 1-in-100 Year Reference Storm and make utilities liable for any negligence setting in geomagnetic latitude scaling factors, ground model scaling factors, transformer screening criteria, transformer thermal assessments, and other factors that could justify not installing automated and near-real-time equipment protection.

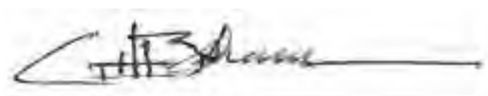
It would be far better for FERC to remand Standard TPL-007-1 than to saddle the public with a reliability standard that would grant liability protection to utilities while blocking the electric grid protection that a 21st century society requires.

Respectfully submitted by:



Thomas S. Popik, Chairman,

William R. Harris, Secretary, and



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Appendix 1

Preliminary Economic Analysis of Electric Grid Protection Against Geomagnetic Disturbance (GMD) Events

by
Jon D. Bate[69]
Prepared for the
Foundation for Resilient Societies, Inc.
52 Technology Way
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Summary:

The financial impact of a severe "1-in-100 year" geomagnetic disturbance (GMD, known commonly as a "solar storm") can be estimated using a parameterized economic model. The economic model assumes that economic activity, as measured by local Gross Domestic Product (GDP) will be seriously degraded in geographic areas that experience a blackout due to GMD effects. GDP will also be affected, but much less significantly, in geographic areas usually engaged in day-to-day commerce with the "blackout region." The model additionally assumes increases in premature mortality ("loss of life") due to blackout conditions and calculates the social cost of deaths using metrics employed by the U.S. government in other cost-benefit analyses.

The economic model indicates that a severe GMD event and resulting wide-area blackout would be extremely costly, both in terms of direct economic losses and also in social cost of lives lost due to increased mortality rates. Economic losses for electric utilities are modeled separately from society as a whole. For utilities, the model assumes financial impacts are principally lost revenue during the blackout duration, as well as grid equipment damaged from GMD and/or associated system collapse.

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[69] Jon Bate, a captain in the U.S. Army, is an unpaid summer intern with the Foundation for Resilient Societies, Inc. He is a second year Master's in Public Policy candidate at the Harvard Kennedy School of Government. The analysis and views expressed do not reflect the position of the U.S. Army, any other federal department or agency, or Harvard University. The author credits the assistance of Resilient Societies staff in developing and refining the economic model.

A 2012 study by the North American Electric Reliability Corporation (NERC) hypothesized that the most likely severe GMD scenario would be system collapse due to voltage instability, with restoration times "a matter of hours to days," if replacement transformers were readily available or unnecessary in most cases.[70] An alternative report commissioned by Oak Ridge National Laboratory and sponsored by the U.S. Department of Energy, U.S. Department of Homeland Security, and Federal Energy Regulatory Commission concluded the most likely scenario is a long-term outage due to extra high voltage transformer damage, with outage periods of months or years.[71] Instead of assuming a single "correct" scenario, the economic model takes the approach of making "duration of outage" a parameter that can be adjusted to reflect the different risk perspectives and economic incentives of utilities and the general public.

Significantly, the economic model is risk-adjusted for the small probability—about 1%-- of a blackout from severe GMD in any single year; therefore, the significant cost of transformer damage for electric utilities is risk-adjusted by a factor of 0.01. However, hardware-based protective cost for transformers, assumed to be the cost of neutral ground blocking devices on a ten-year amortized basis, is modeled as a certainty, without risk adjustment.

Since private utility companies do not bear the full risk-adjusted societal cost of an outage, but only their own risk-adjusted costs, the modeling results (see Figures 1 and 2) show that they have lower economic incentive to protect against GMD events, absent subsidy, strict regulatory standards, and/or legal liability from negligence claims. In contrast, society as a whole has significant economic incentive to protect against even short-term blackouts of one day.

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[70] 2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System," NERC, February 2012, available at https://www.frcc.com/Public%20Awareness/Lists/Announcements/Attachments/105/GMD%20Interim%20Report.pdf

[71] John Kappenman. "Geomagnetic Storms and Their Impacts on the U.S. Power Grid (Meta-R-319)." Metatech. January 2010. Available from http://web.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-319.pdf.

Key Findings:

- A one-day solar storm could cause 163 million people in 25 states and Washington, D.C. to lose power (based on a 50 degree latitude, 4,800 nanoTesla/minute GMD scenario described in Metatech-R-319 report).[72]
- Societal cost of a one-day solar storm power outage is estimated at $35.7 billion (primarily due to lost GDP and loss of life), compared to $3.0 billion for first day losses for private utility companies (the first-day losses for electric utilities result primarily from transformer damage while subsequent losses would be primarily due to lost electricity revenue).[73]
- Power outage scenario results in 574 deaths per day in affected states due to a degraded healthcare system and increase in accidental deaths.
- Investing in protective equipment for at-risk transformers to avoid a one-day outage has a highly favorable benefit-cost ratio (greater than 10) from an overall social perspective.
- Private utility companies are not currently incentivized to protect against a severe GMD event unless it causes a two day outage or greater. A two-day outage would cause an estimated societal cost of $65.5 billion, including 1,147 deaths.

Modeling Assumptions:

- 25 states (and Washington, D.C.) lose power due to voltage collapse and/or permanent transformer damage: Connecticut, Delaware, Georgia, Idaho, Illinois, Indiana, Kentucky, Maine, Maryland, Massachusetts, Michigan, New Hampshire, New Jersey, New York, North Carolina, Ohio, Oregon, Pennsylvania, Rhode Island, South Carolina, Tennessee, Vermont, Virginia, Washington, West Virginia.
- GDP loss: 90% in outage states; 10% loss in non-outage states due to economic interconnectedness.
- At-risk transformer loss: 50% destruction; $5 million cost per transformer.[74]
- Loss per household due to food spoilage and other one-time costs: $48.60.[75]

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[72] Ibid.
[73] Transformer damage of $2.5 billion and residential loss of $3.4 billion are assumed to be one-time costs.
[74] Foundation for Resilient Societies estimate, based on average transformer cost

- Increase in daily mortality rate in outage states is 15%.[76] Cost per life lost: $9.1 million.[77]
- Cost of lost electric utility revenue in affected states: $519 million per day.[78]

Cost-Benefit Analysis of Protection:

Figure 1: Societal Cost-Benefit Analysis

	1 Day Outage	2 Day Outage
GDP Loss	$24.6 billion	$49.2 billion
Transformer Damage	$2.5 billion	$2.5 billion
Residential Losses	$3.4 billion	$3.4 billion
Number of Lives Lost	574	1,147
Social Cost of Lives Lost	$5.2 billion	$26.1 billion
Total Societal Cost	**$35.7 billion**	**$65.5 billion**
Risk-Adjusted Societal Cost	$0.36 billion	$0.66 billion
Total Protective Cost	$0.35 billion	$0.35 billion
Amortized Annual Protective Cost	$0.035 billion	$0.035 billion
Societal Benefit-Cost Ratio	**10.3**	**18.9**

[75] Sullivan, et. al. "Estimated Value of Service Reliability for Electric Utility Customers in the United States." January 2015. http://www.osti.gov/scitech/servlets/purl/1172643. Extrapolated cost of 16 hour outage to a 24 hour period. This is a one-time loss due to loss of perishable goods and increased consumption of stored nonperishable items.

[76] Anderson and Bell. "Lights out: Impact of the August 2003 power outage on mortality in New York, NY." *Epidemiology (Cambridge, Mass)*. 2012;23(2):189-193. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3276729/. Researchers use a regression model to estimate increased mortality in the New York City metropolitan area to be 28% for a one day outage. This model uses a more conservative estimate of 15% since rural areas will be less-affected by a blackout.

The percentage of U.S. population residing in coastal counties adjacent to the Atlantic and Pacific Oceans, the Great Lakes, and the Gulf of Mexico has increased to 29 percent of total U.S. population between the period 1960 and 2008. See the year 2010 Census Bureau report, Coastline Population Trends in the United States: 1960 to 2008. Blackout-related mortality in U.S. coastal counties and densely-populated urban areas may be substantially higher than the 15 percent estimated in this paper, while it may be substantially lower in more rural areas.

[77] "Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analyses." U.S. Department of Transportation. http://www.transportation.gov/sites/dot.dev/files/docs/VSL%20Guidance_2013.pdf

[78] "Retail Electricity Sales Statistics, 2012." Annual Electric Power Industry Report. U.S. Energy Information Administration, Form EIA-861, "Annual Electric Power Industry Report."

Figure 2: Private Utility Cost-Benefit Analysis

	1 Day Outage	2 Day Outage
Loss of Electricity Revenue	$0.52 billion	$1.0 billion
Transformer Damage	$2.5 billion	$2.5 billion
Total Private Utility Cost	**$3.0 billion**	**$3.5 billion**
Risk-Adjusted Private Utility Cost	$0.030 billion	$0.035 billion
Total Protective Cost	$0.35 billion	$0.35 billion
Amortized Annual Protective Cost	$0.035 billion	$0.035 billion
Private Utility Benefit-Cost Ratio	**0.9**	**1.0**

Cost-Benefit Analysis Assumptions:

- $350,000 cost to protect each transformer with neutral blocking equipment.[79]
- Protective equipment cost is amortized over a 10 year useful life.[80]
- Probability of severe solar storm: 1% per year (approximately)—12% per decade.[81]

Conclusions:

Due to the high societal costs of a power outage, federal and state governments have an incentive to protect against even a one-day power outage due to a GMD event. However, private utility companies do not have a business case to invest in protective transformer equipment until the projected outage reaches a minimal duration of two days, assuming there is no cost recovery for protective equipment and also assuming utilities have no exposure to losses from negligent liability claims. Utility losses due to transformer damage and lost electricity revenues are projected to be 7% to 8% of aggregate societal costs the first day of an outage.

[79] Foundation for Resilient Societies estimate based on discussions with manufacturers of protective equipment. Only "at-risk" transformers according to Metatech R-319 report would require protection.
[80] Useful life of blocking equipment would likely exceed 10 years.
[81] Pete Riley. "On the Probability of Occurrence of Extreme Space Weather Events." February 2012. Available from http://onlinelibrary.wiley.com/doi/10.1029/2011SW000734/abstract

By the two-day mark, society faces a cost of $65.5 billion, including over 1,100 lost lives. Absent mandatory governmental regulation, the lack of incentive for private utilities to protect the grid creates a classic "market failure" for grid protection. Protecting the bulk power grid against a severe GMD event creates a positive externality that benefits our electricity-dependent society in the form of avoided power outage costs. Since private utilities do not possess sufficient incentive to invest in the socially optimal level of grid protection, the gap in protection requires government action in the form of subsidy (cost recovery for protective equipment), regulation, and/or establishment of legal liability for negligence.

Appendix 2

Reference Documents

UNITED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

Reliability Standard for Transmission System Planned) Docket No. RM15-11-000
Performance for Geomagnetic Disturbance Events)

<u>Reference Document No. 1</u>

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Foster, John S.; Gjelde, Earl; Graham, William R; Hermann, Robert J.; Kluepfel, Henry M.; Lawson, Richard L.; Soper, Gordon K.; Wood, Lowell L., Jr.; Woodard, Joan B.
Title	Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack: Critical National Infrastructures
Publication Series	www.empcommission.org/reports.php
Date	April 2008
Web click-through	http://www.empcommission.org/docs/A2473-EMP_Commission.pdf
Key findings	Ch. 2, Electric Power, pp. 17-61; Fig. 2-3, GIC Damage to Transformer During 1989 Geomagnetic Storm, p. 33; EMP Comm'n field tests of electrical system components and subsystems substantially less than projected EMP E3 fields, p. 18; GMD storms have caused both transformer and capacitor damage even on properly protected equipment, p. 33; 1 in 100 year GMD storm will cause "hundreds of high voltage transformers to saturate" leading to "voltage collapse in the affected areas and damage to elements of the transmission system," p. 43; likelihood of a blackout lasting years over large portions of the affected region is substantial with damage to these high-value components. The islanding … may help reduce the E2 and E3 impacts…." p. 59
Together with other relevant materials and references.	

UNITED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events	**)** **)**	**Docket No. RM15-11-000**

Reference Document No. 2

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Stockton, Paul; Beck, Chris; and Schnurr, Avi (eds.)
Title	Electric Infrastructure Protection (E-PRO) Handbook
Publication Series	www.eiscouncil.org
Date	1st ed. Dec. 17, 2014
Web click-through	Not available. Hard copies distributed 7-21-15 to FERC Commissioners and staff.
Key findings	Severe GMD durations, p. 72; ch. 2, Power Grid Protection & Restoration, pp. 89-190; E-threat characteristics, pp. 103-108; Fig. 2.3, p. 118 shows high voltage transmission systems at risk; Fig. 2.4, locations of Top 500 GIC Participation transformers in CONUS, p. 119 is inconsistent with NERC GMD benchmark model; during "very large" GMD events, transformers near coasts and in Southeast, Florida, and Gulf of Mexico are included among transformers "most likely to be at risk of excessive, > 90 Amps per phase GIC flow"; proposed selective load shedding for unprotected transformers, p. 126, may be infeasible in limited warning windows with exclusion of generator operators from EOP-010-1 mitigation duties without mandatory GIC data sharing. See pp. 132-136 on derating or disconnection options for unprotected EHV transformers. E-3 protection for GMD will benefit E3 protection for EMP; assess consequences of mitigation hardware for GMD-EMP interactions and cost impacts.
Together with other relevant materials and references.	

UNITED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events	**)** **)**	**Docket No. RM15-11-000**

Reference Document No. 3

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	John Kappenman for Metatech Corp. Meta R-319
Title	Geomagnetic Storms and Their Impact on the US Power Grid
Publication Series	
Date	January 2010
Web click-through	https://www.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-319.pdf
Key findings	GMD threat environment for power grid, pp. 1-1 to 1-31; March 1989 storm impacts, pp. 2-1 to 2-22; sec.2.2.5 increased reactive power demand and concurrent loss of reactive power capacity in solar storms, a missing element of NERC-FERC modeling upon risks of instability, cascading outages and grid separation, pp 2-23 to 2-28; Salem-1 damage, pp. 2-29 to 2-35; threats from extreme geomagnetic storms, pp. 3-1 to 3-30; At-risk extra high voltage transformers, pp. 4-1 to 4-23; instant reactive power demand increases, p. A1-4; App. 2, detailed Summary, Hydro-Quebec Storm, March 13-14, 1989, pp.A2-1 to A2-8; Appendix 3, Benchmarking solar storms, showing broad impacts concurrently, pp. A3-1 to A3-20; App. 4, Validating transformer modeling, pp. A4-1 to A4-23, in contrast with failure of GMD Task Force to validate its model with empirical transformer performance indicators for North America.
Together with other relevant materials and references.	

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Reference Document No. 4

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Frank Koza
Title	NERC GMD Reliability Standards
Publication Series	Idaho National Laboratory
Date	April 8, 2015
Web click-through	Frank Koza presentation on GMD standard
Key findings	
Together with other relevant materials and references.	

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Reliability Standard for Transmission System Planned) Docket No. RM15-11-000
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Reference Document No. 5

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Foundation for Resilient Societies & NERC Staff
Title	NERC Level 1 & 2 Appeal Record in TPL-007-1 Transmission System Planned Performance for Geomagnetic Disturbance Events (Project 2013-03, Geomagnetic Disturbance Mitigation.
Publication Series	
Date	January/February 2015
Web click-through	http://www.nerc.com/pa/stand/project201303geomagneticdisturbancemitigation/2013-03_gmd_level_2_appeal_foundation_for_resilient_societies_tpl-007-1_05182015.pdf. http://www.resilientsocieties.org/uploads/5/4/0/0/54008795/appeals_20150104_nerc_stage_1_appeal_tpl-007-1.pdf http://www.resilientsocieties.org/uploads/5/4/0/0/54008795/letters_20150226_nerc_stage_2_appeal_tpl-007-1.pdf
Key findings	Resilient Societies cites failures of data collection, data sharing, data validation, model validation with empirical data from North America and not Finland and other IMAGE sites in Northern Europe; and failures of quality control by the NERC Office of Standards. The failure to include model elements for Reactive Power Losses, Increased VAR demand, and potential system imbalance impacts on voltage and frequency swings; the absence of vibration modeling; the absence of a coast effect; and bias in other model components drive Benchmark Model postulates to the point that known transformer losses during solar storms – at Wiscasset, Maine (Maine Yankee); Seabrook, NH; and Salem 1 and 2 in New Jersey) and other locations of prior damaged or destroyed transformers are exempt from even “assessment” duties. Procedural failures drive substantive errors with systematic bias against any assessment duty for hardware protection.
Together with other relevant materials and references.	

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Reference Document No. 6

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Central Maine Power Co., by Justin Michlig, with contributions by Emprimus, Maine Public Utilities Commission, et al.
Title	2014 Maine GMD/EMP Impacts Assessment
Publication Series	Maine Public Utilities Commission Filings in MPUC Docket 2013-00415
Date	December 23, 2014
Web click-through	https://www.mpuc-cms.maine.gov. Lookup Docket 2013-00415. Download item 51.
Key findings	GIC has potential to cause disruption to power system operations, by transformer heating, reduced voltage operations and harmonics. p.6. The NERC Benchmark model adjusted for Northern Maine projects maximum of 4.53 volt/km geoelectric field for NERC's claimed 1 in 100 year benchmark storm. p.7. The CMP Study Team assumed 1 in 50 year storm voltage up to 14 volts/km and 1 in 100 year volts/km up to 23.5 volts, p.7. Using the NERC model, no neutral blocking devices or other mitigation hardware would be required in Maine. The 1 in 50 yr storm per CMP modeling would justify $2.8 M of neutral ground blocking for 7 transformers at $350K per unit; 16 GIC monitors, at per unit installed cost of $36K. Susceptible capacitor replacements would cost $1M for 4 capacitors. p.7. Since publication in Dec. 2014 and NERC proposed GMD Hardware standard in Jan. 2015, Central Maine Power has declined to budget for or order protective equipment including neutral ground blockers, despite CMP finding 7 of its transformers would exceed 75 Amps per Phase for both their 1 in 50 year GMD event, and their 1 in 100 year GMD event. See Table 3 at p. 27. These results do not model a "coastal effect" which would place at risk additional transformers, and which may have caused damage to Maine Yankee's GSU 345 kV transformer in March 1989 GMD, loss of that transformer in April 1991 and potential damage to 2 replacement GSU transformers installed in 1993.
Together with other relevant materials and references.	

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Reference Document No. 7

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Emprimus
Title	Effects of GMD and EMP on the State of Maine Power Grid
Publication Series	
Date	January 2, 2015
Web click-through	http://www.maine.gov/tools/whatsnew/attach.php?id=639058&an=2
Key findings	
Together with other relevant materials and references.	

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Reference Document No. 8

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Foundation for Resilient Societies
Title	Economic Model for Mitigation of GMD and EMP
Publication Series	
Date	2015
Web click-through	Resilient Societies EMP GMD Cost Estimate
Key findings	
Together with other relevant materials and references.	

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Reference Document No. 9

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Dr. David Boteler
Title	The impact of space weather on the electric power grid
Publication Series	Heliophysics V. Space Weather and Society
Date	July 7, 2014
Web click-through	http://www.spacewx.net/pdf/HSS5.pdf pp 68-89
Key findings	
Together with other relevant materials and references.	

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Reference Document No. 10

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Carolus J. Schrijver & Sarah D. Mitchell
Title	Disturbances in the US electric grid associated with GMD
Publication Series	J. Space Weather Space Climate
Date	April 19, 2013
Web click-through	http://www.swsc-journal.org/articles/swsc/pdf/2013/01/swsc120066.pdf
Key findings	For the period 1992 thru 2010, with more than 3**σ (sigma)** significance, or odds ratio of 32-to-1, approximately 4% of disturbances in the U.S. power grid reported to the US Department of Energy "are attributable to strong geomagnetic activity and associated geomagnetically induced currents." Abstract. GICs induce thermal effects and reactive power consumption that impacts regional reactive power imbalance s with swings in voltage and frequency. A19p1. Mitigation strategies are warranted. A19p7.
Together with other relevant materials and references.	

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Reference Document No. 11

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Lloyd's; Atmospheric & Environmental Research
Title	Solar Storm Risk to the North American Electric Grid
Publication Series	
Date	2013
Web click-through	Lloyds & AER Report
Key findings	
Together with other relevant materials and references.	

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Reference Document No. 12

Submitted by the Foundation for Resilient Societies
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in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Lloyd's
Title	The insurance implications of a cyber attack on the US power grid
Publication Series	Emerging Risk Report – Innovation Series
Date	July 2015
Web click-through	Lloyds Business Blackout Report
Key findings	
Together with other relevant materials and references.	

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Reference Document No. 13

Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	C.J. Schrijver, R. Dobbins, W. Murtagh, S.M. Petrinec
Title	Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment
Publication Series	Space Weather Journal
Date	June 21, 2014
Web click-through	http://arxiv.org/pdf/1406.7024v1.pdf
Key findings	
Together with other relevant materials and references.	

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Submitted by the Foundation for Resilient Societies
52 Technology Way, Nashua, NH 03060
in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	National Security Telecommunications Advisory Committee
Title	NSTAC Issue Review 06-07
Publication Series	
Date	2007
Web click-through	http://www.dhs.gov/sites/default/files/publications/2006-2007%20NSTAC%20Issue%20Review_0.pdf
Key findings	
Together with other relevant materials and references.	

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Reference Document No. 15

Submitted by the Foundation for Resilient Societies
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in FERC Docket No. RM15-11-000
(filed on July 27, 2015)

Author(s)	Scott Dahman, PowerWorld Corporation
Title	BPA GMD Impact Assessment TIP 264 GIC R&D
Publication Series	
Date	September 30, 2013
Web click-through	http://elibrary.ferc.gov/idmws/common/opennat.asp?fileID=13941706
Key findings	Modeling for voltage collapse.
Together with other relevant materials and references.	

DR. PETER VINCENT PRY

Dr. Peter Vincent Pry is Executive Director of the EMP Task Force on National and Homeland Security, a Congressional Advisory Board dedicated to achieving protection of the United States from electromagnetic pulse (EMP), cyber attack, mass destruction terrorism and other threats to civilian critical infrastructures on an accelerated basis. Dr. Pry also is Director of the United States Nuclear Strategy Forum, an advisory board to Congress on policies to counter Weapons of Mass Destruction.

Dr. Pry served on the staffs of the Congressional Commission on the Strategic Posture of the United States (2008-2009); the Commission on the New Strategic Posture of the United States (2006-2008); and the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack (2001-2017) as Chief of Staff.

Dr. Pry served as Professional Staff on the House Armed Services Committee (HASC) of the U.S. Congress, with portfolios in nuclear strategy, WMD, Russia, China, NATO, the Middle East, Intelligence, and Terrorism (1995-2001). While serving on the HASC, Dr. Pry was chief advisor to the Vice Chairman of the House Armed Services Committee and the Vice Chairman of the House Homeland Security Committee, and to the Chairman of the Terrorism Panel. Dr. Pry played a key role: running hearings in Congress that warned terrorists and rogue states could pose an EMP threat, establishing the Congressional EMP Commission, helping the Commission develop plans to protect the United States from EMP, and working closely with senior scientists who first discovered the nuclear EMP phenomenon.

Dr. Pry was an Intelligence Officer with the Central Intelligence Agency responsible for analyzing Soviet and Russian nuclear strategy, operational plans, military doctrine, threat perceptions, and developing U.S. paradigms for strategic warning (1985-1995). He also served as a Verification Analyst at the U.S. Arms Control and Disarmament Agency responsible for assessing Soviet compliance with strategic and military arms control treaties (1984-1985).

Dr. Pry has written numerous books on national security issues, including: *POSEIDON: Russia's New Doomsday Machine; The Long Sunday: Nuclear EMP Attack Scenarios; Blackout Wars; Apocalypse Unknown: The Struggle To Protect America From An Electromagnetic Pulse Catastrophe*; *Electric Armageddon: Civil-Military Preparedness For An Electromagnetic Pulse Catastrophe*; *War Scare: Russia and America on the Nuclear Brink*; *Nuclear Wars: Exchanges and Outcomes*; *The Strategic Nuclear Balance: And Why It Matters*; and *Israel's Nuclear Arsenal*. Dr. Pry often appears on TV and radio as an expert on national security issues. The BBC made his book *War Scare* into a two-hour TV documentary *Soviet War Scare 1983* and his book *Electric Armageddon* was the basis for another TV documentary *Electronic Armageddon* made by the National Geographic.

Dr. Peter Pry

***This recognizes Dr. Peter Pry** for his outstanding accomplishments during his 10 years of service at the Central Intelligence Agency. A noted expert in his field, Dr. Pry conducted groundbreaking research that illuminated one of the most important issues of our time—the US-Soviet nuclear competition. On the vanguard of strategic intelligence analysis during the Cold War, he developed much of what the US Government knows about Soviet planning for nuclear war, including Soviet views of the character of war, perceptions of US intentions, assessment of the nuclear balance, and operational plans. In the post-Cold War period, his work has been central to the US Government's understanding of evolving Russian threat perceptions and military doctrine and the construction of new paradigms for strategic warning and stability assessments.*

Dr. Pry can take pride in knowing that his work has contributed significantly to the security of the United States. He has been a pillar of the Intelligence Community and will be sorely missed. Without a doubt, his continued public service on Capitol Hill will reflect the same expertise, professionalism, and dedication that have characterized his exemplary career at the CIA.

We wish him much success in his new endeavor.

Lawrence K. Gershwin	*Charles E. Allen*	*John E. McLaughlin*

DR. WILLIAM R. GRAHAM

Dr. William R. Graham is Chairman of the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack. He was Chairman of the Board and Chief Executive Officer of National Security Research Inc. (NSR), a Washington-based company that conducts technical, operational, and policy research and analysis related to US national security.

Previously he served as a member of several high-level study groups, including the Department of Defense Transformation Study Group, the Defense Science Board, the Commission to Assess United States National Security Space Management and Organization (the Rumsfeld Commission on Space), the Commission to Assess the Ballistic Missile Threat to the United States (also led by Hon. Donald Rumsfeld), and the National Academies' Board on Army Science and Technology. From 1986–89 Dr. Graham was the Director of the White House Office of Science and Technology Policy while he served concurrently as Science Advisor to President Reagan, Chairman of the Federal Joint Telecommunications Resources Board, and member of the Arms Control Experts Group. Before going to the White House, he served as the Deputy Administrator of NASA. For 11 years, he served as a member of the Board of Directors of the Watkins-Johnson Company.