UNITED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

Grid Resilience in Regional Transmission	**)**	**Docket No. RM18-1-000**
Organizations and Independent System	**)**	**Docket No. AD18-7-000**
Operators.	**)**	

COMMENTS OF MICHAEL MABEE

Submitted to FERC on May 9, 2018

Michael Mabee respectfully submits comments on FERC Docket No. RM18-1-000 and Docket No. AD18-7-000, Grid Resilience in Regional Transmission Organizations and Independent System Operators.

Background:

I am a private citizen with expertise on emergency preparedness, specifically on community preparedness for a long-term power outage. My career includes experience as an urban emergency medical technician and paramedic, a suburban police officer, and in the federal civil service. In the U.S. Army, I served in two wartime deployments to Iraq and two humanitarian missions to Guatemala. I retired from the U.S. Army Reserve in 2006 at the rank of Command Sergeant Major (CSM). I was decorated by both the U.S. Army and the federal government for my actions on 9/11/2001 at the World Trade Center in New York City. In sum, I have a great deal of experience – both overseas and in the U.S. – working in worlds where things went wrong.

I have studied the vulnerabilities of the U.S. electric grid to a variety of threats. My research lead me to write two books about how communities can prepare for and survive a long term power outage.[1] I continue to write extensively on emergency preparedness for blackout.

Newly Available EMP Commission Reports

On May 8, 2018 the Department of Defense ("DoD") released three reports from the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack ("EMP Commission"). The EMP Commission is a commission chartered by Congress to study Electromagnetic Pulse (EMP), geomagnetic disturbance (GMD), and other threats to the electric grid and critical infrastructures. These three recently released reports (all dated July 2017) are among 10 new reports from the EMP Commission that have been withheld until the DoD "declassifies" and releases them.

I believe that these new reports are critical to inform FERC and the public about the threats to our critical electric infrastructure. I am filing this comment to put these three reports into the record for this docket:

Appendix 1: Assessing the Threat from Electromagnetic Pulse (EMP) Executive Report
Appendix 2: Life without Electricity: Storm-Induced Blackouts and Implications for EMP Attack
Appendix 3: Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures

These recently released reports are critical to rebut the "false science" being put out by the electric utility industry. FERC should weigh any purported scientific claims by the electric industry against the credible and expert findings of the EMP Commission.

It is difficult to overstate the importance of the security and reliability of the U.S. electric grid. Our ability to maintain our present human population depends on the electric grid. Significantly, the EMP Commission notes:

> *"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."* Appendix 1, page 4. [Internal references omitted.]

<u>Conclusion</u>:

FERC is charged with serving the public interest. Not the interests or convenience of the electric utility industry. The public interest demands that the federal government insure that the critical infrastructures are adequately protected against known threats, such as EMP and GMD. I believe the attached EMP Commission reports are critical to FERC's evaluation of grid resilience.

Respectfully submitted by:

Michael Mabee

Attachments

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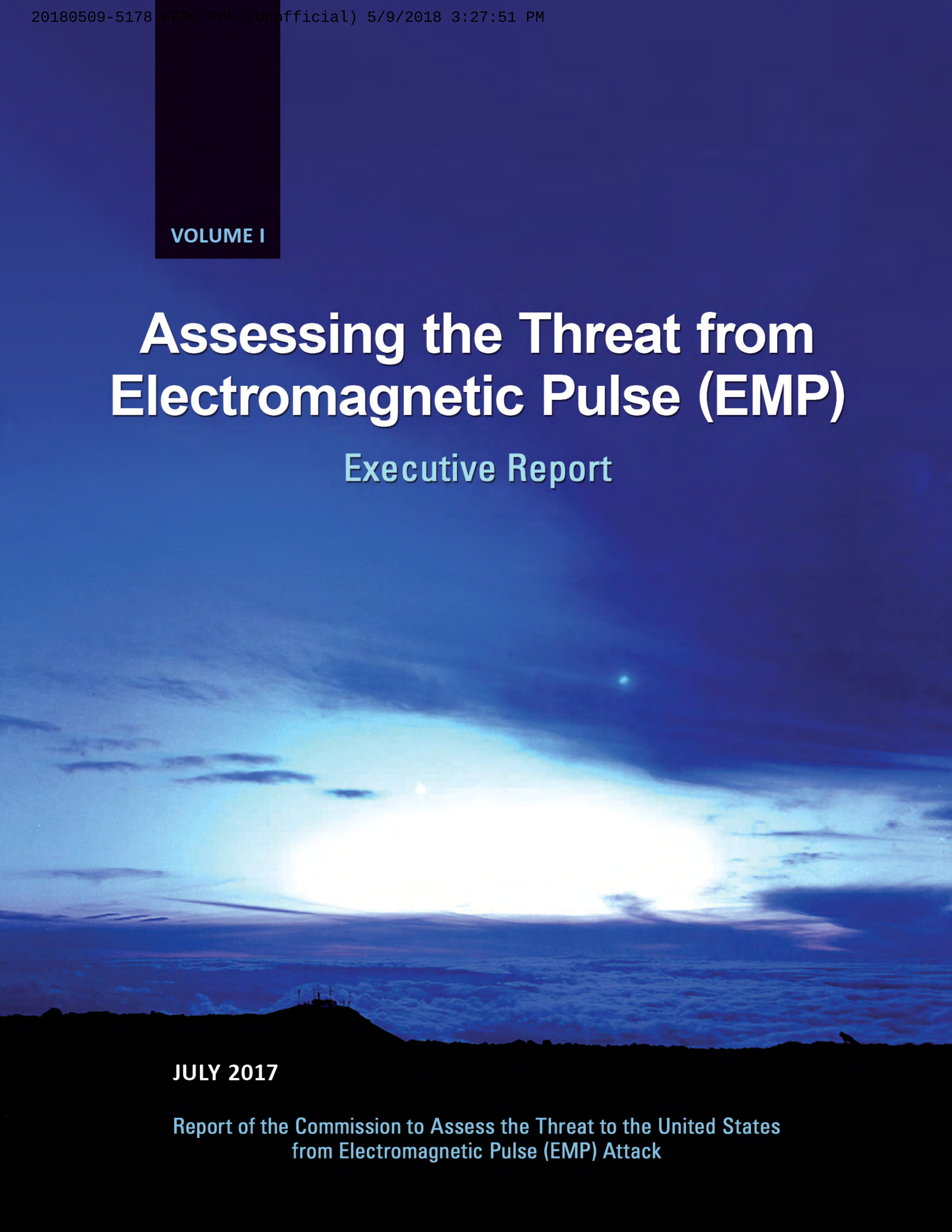
[1] Mabee, Michael. *The Civil Defense Book: Emergency Preparedness for a Rural or Suburban Community*. ISBN-13: 978-1974320943, first edition published July 4, 2013, second edition published October 17, 2017.



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

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.

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

[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

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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

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 electronic systems.

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

[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.

[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 or low-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]

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 EMP 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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P.V. Pry. Life without Electricity: Storm Induced Blackouts and Implications for Electromagnetic Pulse Attack, 2017

P.V. Pry. Nuclear Terrorism and Electromagnetic Pulse Attack, 2017

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LIFE WITHOUT ELECTRICITY:

STORM-INDUCED BLACKOUTS AND IMPLICATIONS FOR EMP ATTACK

by

Dr. Peter Vincent Pry

July 2017

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

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

LIFE WITHOUT ELECTRICITY:

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Dr. Peter Vincent Pry

July 2017

This paper was drafted on June 20, 2003 to inform the work of the EMP Commission during 2001-2008, but could not be published because the Commission was terminated before Staff Papers could be submitted for security classification review. It is offered now for completeness of the analytical record.

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 was produced to support 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.

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Table of Contents

Summary

Storm-induced blackouts of the electric power grid are suggestive of the possible consequences of an electromagnetic pulse (EMP) attack, such as could be made by rogue states or terrorists detonating a nuclear weapon at high-altitude over the United States. Electric power grid failure caused by storms cascade through other critical infrastructures—such as communications, transportation, emergency medical services, food and water supply systems. Storm-induced blackouts provide an objective basis for extrapolating judgments about the threat posed by EMP to the civilian infrastructures that sustain economic, political, and social life.

The vulnerability of critical infrastructures to various forms of attack has been a growing concern in recent years, drawing presidential attention in the Marsh Commission, and receiving additional impetus after the terrorist attacks of September 11th that moved President Bush to establish the Department of Homeland Security. However, the science of analyzing critical infrastructures, their interdependencies, and their possible vulnerabilities is relatively new. Much effort and significant resources have been invested in an inductive approach to understanding the potential for cascading failures through the critical infrastructures that may result from failure of the power grid. The prevailing approach relies heavily on complex mathematical calculations, theoretical models, and computer simulations.

Analysis of storm-induced blackouts and their consequences offers an empirical approach that complements the predominant inductive approach to understanding infrastructure interdependence and vulnerability. Moreover, beyond the interdependence and potential vulnerability of critical infrastructures, analysis of storm-induced blackouts provides some empirical basis for estimating the effects of infrastructure failure on social order.

Storm-induced blackouts are an imperfect analogy to EMP attack from nuclear weapons of high-yield or special design. Taken at face value, storm-induced blackouts and their consequences grossly understate the threat posed by EMP attack. Storms are much more limited in geographic scope compared to EMP attack. So power grid recovery from storms, compared to recovery from EMP attack, is likely to be faster because of the "edge effect"—the capability of neighboring localities and states to provide recovery assistance. Because EMP attack is likely to damage or disrupt electronics over a much wider geographic area than storm-induced blackouts, rescuers from neighboring states and localities would face a much bigger job, and recovery probably would take a much longer time.

Nor do storm-induced blackouts replicate the damage from an EMP attack that may occur in small-scale electronic systems such as computers, aircraft, and automobiles. Compared to storms, nuclear weapons of high-yield or special design are likely to inflict, not only more widespread damage geographically, but deeper damage, affecting a much broader spectrum of electronic equipment.

Storms are merely suggestive of, and provide some basis for extrapolating, the greater destructive effects on infrastructures and social order by an EMP attack from a nuclear weapon

of high-yield or special design. Storm-induced blackouts and their consequent physical damage to other infrastructures may well be equivalent to an EMP attack from a nuclear weapon of low-yield and primitive design, such as terrorists might be able to build. In this latter case, storm-induced blackouts and the cascading physical effects on other infrastructures may be taken as representative of the lowest, and most benign, level of the EMP threat spectrum.

However, although some storms may be equivalent to a primitive EMP attack in their physical damage to the power grid and other infrastructures, storms probably understate even a primitive EMP attack in its psychological dimensions. Unlike EMP attack, hurricanes and other storms are familiar to the public and understood to be acts of nature, not the destructive agents of a foreign enemy. Public perceptions of and reactions to mass destruction differ markedly when the agent of destruction is a familiar natural event or accident, versus destruction by unfamiliar means inflicted deliberately by malignant actors. For example, the American people endure tornadoes and hurricanes without mass panic, and accept with equanimity 50,000 deaths yearly from automobile accidents. But the same number of deaths inflicted over a decade by a foreign enemy was enough to cause a political and cultural revolution in the United States, and broke the will of the people and political elites who accepted defeat in the Vietnam War. More recently, the 3,000 deaths and other destruction inflicted by the terrorist attacks of September 11 have moved the United States, with wide popular support, to prosecute successful wars in Afghanistan and Iraq as part of a broader ongoing war against terrorism. The United States government and people support this effort because, although U.S. society can survive the worst hurricane, the September 11 events forged a new consensus that U.S. society, and civilization itself, may not be able to survive future terrorist attacks.

Psychologically benign though storms may be, compared to terrorist attacks that inflict lesser or greater physical destruction, even storms challenge social order. This survey has found that some storm-induced blackouts have caused crime waves and disintegrated organized communities into disorganized refugees, for example.

Significantly, some observers of storm-induced blackouts—even when blackouts lasted only a day or two, as is commonly the case—were struck by the potential fragility of modern society and its near total dependence upon electricity. For example, a January 1999 ice storm that blacked-out electricity in the Washington, D.C. area moved the **Washington Post** to note that "daily life was crippled, if not halted—dramatically illustrating the fragile dependence of modern times on the flip of a switch."[1] The *Post* continued:

> *Automated teller machines were out, as were gasoline pumps at many service stations. WETA-TV (Channel 26) went black for more than 10 hours until employees found a diesel generator to put that station back on the air. The Montgomery County jail conducted bond hearings by flashlight. Families seeking refuge at Tysons Corner Center were booted out at 6 p.m. because of*

[1] Susan Levine and Tom Jackman, "Region Iced Over and Blacked Out," **Washington Post** (16 January 1999), p. A1.

> *water problems at the mall….Up and down Metro's Red Line, riders confronted stalled elevators, inoperable Farecard machines and even closed stations. Negotiating roads…was often no easier. Of more than 700 traffic signals in Montgomery, 430 were dead. Across the area, but especially in Montgomery, hotels filled to capacity with customers fleeing cold, dark homes. The 365-room Doubletree Hotel on Rockville Pike was sold out by 8 a.m.….Other residents, with pioneering spirit, decided to ride out the outage. More than two dozen people were waiting when the Home Depot in Germantown opened at 6 a.m.. By 10 a.m., the store had sold every generator, log of firewood, candle, kerosene heater and any other supply that could warm hands and feet.*[2]

Another dramatic example of the dependency of social order upon electricity occurred in October 2002, during the aftermath of Hurricane Lili that blacked-out much of coastal Louisiana. In some areas, the absence of street lights caused "looting and vandalism bad enough to require enforcement of a dusk-to-dawn curfew."[3] Local police had to be reinforced by police from neighboring localities in order to cope with the crime wave. "The looting," remarked Abbeville Mayor Mark Piazza, "Is not expected to go away until the lights come on."[4]

Some experts claim that an EMP attack that collapses the power grid would, in effect, return society to a pre-industrial condition. A February 1987 snowstorm that blacked-out the Washington, D.C. area suggested exactly this to many of its victims. According to press reports, people were reduced to using open fires for heat, cooking and, in some areas, melting snow for water. Homes with fireplaces became havens for multiple families seeking refuge from houses heated by electric, gas, or oil that no longer worked. As she "stoked a fire and began sterilizing water for her baby's formula," one woman told reporters, "It's like the Colonial days."[5]

Storm-induced blackouts are localized and last usually no more than a day or two. Yet they can momentarily return part of our society to technological primitivism and begin cracks in the social order. Compared to storms, the consequences of an EMP attack would be far graver. Compared to the worst storms, an EMP attack would probably destroy infrastructures more completely within a region and over a much larger region—perhaps over the entire continental United States. An EMP attack, compared to the worst storms, would probably inflict more lasting damage—requiring perhaps weeks or months to repair.

Therefore, we can reasonably infer from the data on storm-induced blackouts and the known greater severity of high-altitude nuclear EMP that the consequences of an EMP attack on the United States' infrastructures and society would be an unprecedented and first order catastrophe.

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2 Ibid.
3 Leslie Williams, "One Town's Battle," **Times-Picayune** (9 October 2002), p. 1.
4 Ibid.
5 John Lancaster and Chris Spolar, "Washington's Wet Blanket," **Washington Post** (24 February 1987), p. 1.

Some of the salient infrastructure and social consequences of storm-induced blackouts are listed below. Not all of the failures and effects described occurred during all storms. This survey was careful to select only failures and effects traceable to power grid failure. Failures and effects resulting from phenomenon other than electric power grid blackout (downed trees, flooding and etc.) are not reported here. Storm- and weather-related blackouts examined in this survey include Hurricane Lili (2002), Hurricane Floyd (1999), the Washington Ice Storm of 1999, the Great Ice Storm of 1998, the Western Heat Wave of 1996, and Hurricane Andrew (1992):

- **Social Order:** Looting requires dusk to dawn curfew. People become refugees as they flee powerless homes. Work force becomes differently employed at scavenging for basics, including water, food, and shelter.
- **Communications:** No TV, radio, or phone service.
- **Transportation:** Gas pumps inoperable. Failure of signal lights and street lights impedes traffic, stops traffic after dark. No mass transit metro service. Airlines stopped.
- **Water and Food:** No running water. Stoves and refrigerators inoperable. People melt snow, boil water, and cook over open fires. Local food supplies exhausted. Most stores close due to blackout.
- **Energy:** Oil and natural gas flows stop.
- **Emergency Medical:** Hospitals operate in dark. Patients on dialysis and other life support threatened. Medications administered and babies born by flashlight.
- **Death and Injury:** Casualties from exposure, carbon dioxide poisoning and house fires increase.
- **Edge Effect:** Recovery depends heavily on neighboring regions unaffected by blackout. For example, Louisiana rescued from Hurricane Lili blackout by 14,000 workers from 24 states.

Hurricane Lili (October 2002)

Hurricane Lili struck the coast of Louisiana on October 3, 2002, coming ashore at Vermillion Bay, the eye of the storm centered on Abbeville about 90 minutes after landfall.[6] Lili knocked down 35 transmission lines and destroyed 53 electric power substations.[7] More than 500,000 people were without electric power at the height of the blackout, immediately after the storm.[8] Three days later, on October 6, over 100,000 homes and businesses were still without power in coastal Louisiana, according to the state Office of Emergency Preparedness.[9] Six days after Lili, on October 9, in Abbeville and surrounding Vermillion Parish, an estimated 80 percent of the 20,000 homes and 50 percent of businesses were still without electricity.[10]

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6 Williams, op. cit., p. 1.
7 Angela Simoneaux, "Flooded, Battered La. Gets Busy Cleaning Up," **Morning Advocate** (5 October 2002), p. 1A.
8 Angela Simoneaux, "Acadiana's Recovery," **The Advocate** (8 October 2002), p. 5B.
9 Kevin McGill, "Rise Seen In Carbon Monoxide Poisoning Cases," **The Advocate** (7 October 2002), p. 2B.
10 Williams, op. cit., p. 1.

As a consequence of the blackout, water and food were unavailable through the normal means to thousands. With no electricity, water pumping stations no longer worked. In south Louisiana, 30 supermarkets would not open because the blackout prevented their cash registers from operating. Those grocery stores that did open were stripped of food within hours. In Abbeville, the parking lots of shopping centers became watering and feeding stations run by churches and the state Office of Emergency Preparedness. Associated Grocers, that supplies food to supermarkets in Louisiana, Texas, and Mississippi, sent food and refrigerated trucks to the stricken area. The food emergency was reflected in a skyrocketing demand for dry ice to preserve food stuffs during the hot weather and to preserve refrigerated foods. Local supplies of dry ice were exhausted--one store selling 20,000 pounds of dry ice to hundreds of customers in two hours—and had to be supplemented with supplies from the Red Cross.[11]

The electrical outage deprived thousands of phone service for days after the Hurricane.[12] Television service was also blacked out.[13]

The blackout interfered with transportation by rendering signal lights inoperable.[14] Street lights were also inoperable, making driving at night difficult even for long-time local residents, who could not see landmarks and became disoriented in the dark.[15]

Power grid collapse caused failure in other energy infrastructures. Without electricity, natural gas service could not be restored for several days after Lili.[16]

Many hospitals were plunged into darkness during the blackout because they had no emergency generators or emergency power systems failed to work. There was no hot water for bathing patients or sterilization. "We have to give them medicines in the dark," said one nurse, "We use a flashlight to make sure we don't give them the wrong one."[17]

The blackout caused indirectly some injuries and at least one death. Home generators used by people who lost power after Hurricane Lili led to more than 60 cases of carbon monoxide poisoning, including one fatality, according to Louisiana health officials.[18]

Some officials and citizens considered the blackout the worst part of Hurricane Lili. According to Mayor Chuck Butterfield, "We've taken electricity for granted and living without it for three or four days is devastating."[19] Law enforcement officers blamed a surge of looting and vandalism on the blackout. The crime wave became bad enough to require the imposition of a dusk-to-dawn curfew and police reinforcements from neighboring areas unaffected by the storm.

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11 Simoneaux, "Acadiana's Recovery," p. 5B. Williams, op. cit., p. 1. Simoneaux, "Flooded, Battered La. Gets Busy Cleaning Up," p. 1A. Suzan Manuel, "Lili Leaves Residents Powerless," **Daily Town Talk** (5 October 2002), p. 1A. Suzan Manuel, "Thousands Still Without Electricity Across Central La.," **Daily Town Talk** (6 October 2002), p. 8A.

12 McGill, op. cit., p. 2B.

13 Simoneaux, "Acadiana's Recovery," p. 5B.

14 Manuel, "Lili Leaves Residents Powerless," p. 1A.

15 Williams, op. cit., p. 1.

16 McGill, op. cit., p. 2b.

17 Manuel, "Lili Leaves Residents Powerless," p. 1A.

18 McGill, op. cit., p. 2B.

19 Manuel, op. cit. p. 8A.

"The looting," according to the Abbeville Sherriff's Office, "Is not expected to go away until the lights come back on."[20]

Recovery from the blackout, described by a CLECO electric utility spokesman as "the biggest customer outage event in our history," depended heavily on outside assistance.[21] Some 14,000 electric utility workers from 24 states and the District of Colombia joined CLECO's 3,000 workers to make recovery possible in about one week.[22]

Hurricane Floyd (September 1999)

Expected to be a "killer storm" of rare power and destruction, when Hurricane Floyd made landfall near Cape Fear, North Carolina on September 16, 1999, it had subsided into a tropical storm that inundated much of the east coast with heavy rainfall and flooding. But there was little of the destruction anticipated by federal and state authorities that had prompted them to evacuate over 3 million people from the hurricane's path.[23]

Floyd did blackout electrical grids in many areas. However, the consequences of those blackouts for other infrastructures and for society are difficult to evaluate since blackouts tended to occur in areas where the population had already evacuated. Blackouts did interrupt phone service in North Carolina.[24] In Salisbury, North Carolina, more than 200 of 1,200 supermarkets were put out of operation by protracted blackouts, causing substantial food spoilage despite emergency efforts undertaken before the storm to preserve perishable goods in freezers.[25] Most cable TV customers lost service in Baltimore due to a blackout.

Floyd blackouts are notable for causing water treatment and sewage plants to fail in some Virginia localities and, most notably, in Baltimore. Blackout induced failure of Baltimore's Hampden sewage facility for several days raised concerns about a threat to public health. With its three pumps inoperable, Hampden spilled 24 million gallons of waste into Baltimore's Jones Falls waterway and the Inner Harbor.[26]

Perhaps Floyd's blackouts are most significant for complicating the largest evacuation and return of civilians in United States history. Electrical outages apparently prevented many from finding shelter—some traveled over 500 miles seeking accommodations, and found none. Blackout induced failure of traffic signals contributed to some of the largest traffic jams in the

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20 Williams, op. cit., p. 1.

21 Simoneaux, "Flooded, Battered La. Gets Busy Cleaning Up," p. 1A.

22 Keith Darce, "Lights Blink Out All Over Louisiana," **Times-Picayune** (4 October 2002), p. 1. "Lili Left Half A Million Without Power," **Associated Press** (4 October 2002).

23 Brad Liston, Melissa August, Delphine Matthieussent, and Timothy Roche, "A Very Close Call," **Time** (27 September 1999), p. 34.

24 Amanda Milligan Hoffman and Sally Roberts, **Business Insurance** (Crain Communications: 1999).

25 Ibid.

26 Governors James Hunt and James Gilmore interviewed, "Hurricane Floyd Leaves Lingering Questions About Public Policy," **CNN Crossfire** (16 September 1999). Del Quentin Wilber, "Jones Falls Sewage Spill Lasts 2 Days," **Baltimore Sun** (19 September 1999), p. 1A.

nation's history as evacuees tried to return home. For example, one traffic jam on Interstate 10 from the Carolinas to Florida stretched 200 miles.[27]

Ice Storm Washington, D.C. (14 January 1999)

On January 14, 1999, an ice storm downed 250 high-voltage power lines in Washington D.C. and the neighboring suburbs in Maryland and Northern Virginia, causing what the Potomac Electric Power Company (PEPCO) described as "the worst power outage in the utility's 102-year history."[28] The blackout left 435,000 homes and businesses without power. Recovery took six days.[29]

Warm food, potentially a survival issue in the freezing winter conditions, was not available in most people's homes because electric ovens and microwaves no longer worked. Most gas-powered ovens also would not work because those built since the mid-1980s have electronic ignition and cannot be lit with a match.[30] Some resorted to cooking on camp stoves. Preserving refrigerated foods was also a concern that PEPCO tried to help address by giving away 120,000 pounds of dry ice, all it had.[31] Dry ice became a precious commodity.[32]

The blackout crippled ground and rail transportation. Gasoline pumps were rendered inoperable. Non-functioning traffic lights snarled traffic:

> *Up and down Metro's Red Line, riders confronted stalled elevators, inoperable fare card machines and even closed stations. Negotiating roads…was often no easier. Of more than 700 traffic signals in Montgomery, 430 were dead….Arlington County motorcycle officers proved especially resourceful, borrowing portable generators from the public library system to help run traffic lights at four major intersections.*[33]

A local television station, WETA-TV, went off the air for more than 10 hours because of the blackout.[34]

At least one hospital was blacked out. Babies were born by flashlight.[35] Emergency medical services suffered to such an extent that patients requiring life support were put at risk, PEPCO admitted:

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[27] Liston and et. al., op. cit., p. 34. Aaron Steckelberg, "Scenes From The Coast," **Atlanta Constitution** (16 September 1999), p. 10A.

[28] Scott Wilson, "From Ice Storm To Firestorm," **Washington Post** (31 January 1999), p. A1. Manuel Perez-Rivas, "Six-Day Power Outage Is Over," **Washington Post** (21 January 1999), p. B1.

[29] Ibid.

[30] Phillip P. Pan and Spencer S. Hsu, "Without Power, Thousands Wait In Hotels, Malls And Cold Homes," **Washington Post** (17 January 1999), p. A1.

[31] Perez-Rivas, op. cit., p. B1.

[32] Wilson, op. cit. (31 January 1999), p. A1.

[33] Susan Levine and Tom Jackman, "Region Iced Over and Blacked Out," **Washington Post** (16 January 1999), p. A1.

[34] Ibid.

[35] Wilson, op. cit. (31 January 1999), p. A1.

The extent of damage caused by last week's ice storm prevented PEPCO and other area utilities from giving priority to customers with serious medical conditions, including those on life-support systems or dialysis machines, company executives said yesterday.[36]

Ice storm induced blackout in freezing conditions posed a threat to life. Hypothermia surged among the elderly, trapped in their unheated homes. People tried to stay warm by burning charcoal indoors, causing an increase in carbon monoxide poisoning and house fires:

At least a dozen houses…in Montgomery were damaged by fires caused by residents' efforts to stay warm or cook…after burning charcoal indoors. More than a hundred people spent Friday night in emergency shelters…Hospitals reported an influx of elderly in their emergency rooms.[37]

In Maryland, the blackout moved Governor Parris Glendening to declare a state of emergency in six counties. The Governor activated the National Guard to assist firehouses.[38]

The power outage created a refugee population "of entire neighborhoods…searching for warmth and diversion at hotels, theaters, malls and even office towers."[39] Thousands were "fleeing cold, dark homes," according to press reports:

Across the area, but especially in Montgomery, hotels filled to capacity with customers fleeing cold, dark homes. The 365-room Doubletree Hotel on Rockville Pike was sold out by 8 a.m.. Residence Inn by Marriott, on Wisconsin Avenue in Bethesda, with 187 rooms, was sold out by noon.[40]

The blackout moved the **Washington Post** to observe that "daily life was crippled, if not halted—dramatically illustrating the fragile dependence of modern times on the flip of a switch."[41]

The Great Ice Storm (January 1998)

Starting on January 4th and for six days, until January 10, 1998, freezing rain fell across a 600-mile weather front that included parts of Ontario and Quebec in Canada, and Maine and upstate New York in the United States. Electric outages in the affected areas of Canada deprived 4.7 million people, or 16 percent of the Canadian population, of power, according to Emergency Preparedness Canada. In the United States, 546,000 people were without power (deprived of heat, light, and in many instances water) in the cold of mid-winter.[42]

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36 Scott Wilson, "Utilities Say Blackout Overwhelmed Medical Priorities," **Washington Post** (22 January 1999), p. B3.
37 Pan and Hsu, op. cit., p. A1.
38 Ibid
39 Ibid.
40 Ibid. Levine and Jackman, op. cit., p. A1.
41 Levine and Jackman, op. cit., p. 1.
42 Eugene L. Lecomte, Alan W. Pang, and James W. Russell, **Ice Storm '98** (Institute for Business and Home Safety: December 1998), pp. 1-2.

Some of the 5.2 million people affected by the Great Ice Storm of 1998 went without power for five weeks. It was the greatest natural disaster in Canadian history, and generated more insurance claims than Hurricane Andrew, the costliest natural disaster in U.S. history.[43]

One historian of the Great Ice Storm notes that "the storm's biggest impact was, in a sense, not weather-related: It was the loss of electricity":

> *Ice accumulations caused the collapse of more than a thousand…transmission towers…More than 7,500 transformers stopped working….Some parts of Monteregie, a region of 1.3 million people southeast of Montreal, went without power for so long that the area became known as "the Dark Triangle."*[44]

The blackout caused an immediate and life-threatening emergency in Montreal's water supply that depended upon electricity for filtration and pumping. At 12:20 P.M. on January 9th, the two water filtration plants that served 1.5 million people in the Montreal region went down, leaving the area with only enough water to last 4 to 8 hours. Government officials kept the water crisis secret, fearing public knowledge would exacerbate the crisis by water hoarding. However:

> *Even as officials deliberated, water pipes in some households were already dry. As reports and rumors of a water shortage spread, consumption jumped by 10 percent anyway, and bottled water disappeared from stores.*[45]

The **Toronto Star**, in an article entitled "Millions Shiver In Dark: How A Major City is Being Crippled by Deadly Ice Storm," reported that parts of Montreal had run out of water, "and those who still had it were warned not to drink tap water without boiling it first." [46] But most people had no way of boiling water.

Officials feared not only a shortage of drinking water, but an inadequate supply of water for fighting fires. So desperate was the situation that Alain Michaud, Fire Chief of Montreal, prepared to fight fires with a demolition crane instead of water, hoping that "if a building caught fire, it might burn to the ground, but the crane would demolish neighboring structures to prevent the fire's spread."[47] By 9:30 P.M. on January 9th, one of Montreal's major reservoirs was nearly empty. Provincial officials considered evacuating the city. However, Hydro-Quebec, the government electric utility, managed to restore power to the filtration plants and restore water service.[48]

The blackout also threatened the food supply: "Food poisoning has become a real threat as embattled Montrealers, unable to get to stores, eat food that has been kept too long in

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43 Jacques Leslie, "Powerless," **Wired** (April 1999), p.120.
44 Ibid.
45 Ibid, p. 176.
46 Sandro Contenta, "Millions Shiver In Dark: How A Major City Is Being Crippled By Deadly Ice Storm," **Toronto Star** (10 January 1998), p. A1.
47 Leslie, op. cit., p. 176.
48 Ibid.

refrigerators that don't work."[49] In upstate New York, the electric utility Niagara Mohawk announced that it was focusing restoration of electric power on more populated areas "so that supermarkets, gasoline stations and hotels could reopen, and people in the more rural areas could find food and shelter."[50] New York State Electric and Gas helped customers get to shelters and distributed 200,000 pounds of dry ice for storing food."[51] One typical resident of Canada's "Dark Triangle" complained, "I've lost all my food…I melt ice for water. It's no way for a family to live."[52]

Shelter, another basic necessity for survival, was also threatened by the mid-winter blackout: "People without power discovered just how many facets of their lives depended on electricity. Their stoves, appliances, and heating didn't work."[53] Many of Canada's newer, well-insulated homes relied on inexpensive electric heat.[54] Thousands of people fled their cold, dark homes to seek refuge in government and charitable shelters. The situation in Saint-Jean-sur-Richelieu, a working-class town of 36,000 was typical, where 3,600 people became shelter refugees, one-tenth of the population.[55] St. Hyacinthe in the "Dark Triangle" lost nearly half its residents, who mostly fled the city.[56] About 100,000 people took refuge in shelters.[57]

Communications, financial, and transportation infrastructures failed massively during the blackout. In upstate New York, only French Canadian radio stations were still on the air. In Ontario, 50,000 telephones went dead, frustrating the electric utility from restoring power service, since it relied on customer phone calls to locate power failures. Credit cards and ATM machines became useless, so all financial transactions had to be in cash.[58] The blackout shut down Montreal's four subway lines for the first time in the system's 30-year history.[59]

Underscoring that the blackout, not the ice storm, was the real crisis, the Canadian Premier Lucien Bouchard declared that "the most urgent need" was for generators, and appealed to anyone in Canada with a generator to help.[60] Bouchard also appealed to the U.S. Federal Emergency Management Agency, "asking for beds and generators to provide shelters with heat and light."[61]

Hospitals in Canada and the United States were nearly overwhelmed with blackout victims. In Maine, where six out of ten residents lost power, a single hospital, in Lewiston, reported

49 Contenta, op. cit., p. A1.
50 "Monster Ice Storm Slays Transmission Facilities In Quebec, Upstate New York," **Northeast Power Report** (McGraw-Hill: 16 January 1998), p. 1.
51 "Canada And New England Still Reeling," **Electric Utility Week** (19 January 1998), p. 1.
52 Jack Beaudoin, "Quebec In Crisis," **Portland Press Herald** (8 February 1998), p. 45.
53 Leslie, op. cit., p. 176.
54 Beaudoin, op. cit., p. 45.
55 Leslie, op. cit., p. 178.
56 Beaudoin, op. cit., p. 45.
57 Leslie, op. cit., p. 122.
58 Ibid, p. 176.
59 Contenta, op. cit., p. A1.
60 Mark Dunn, "Ice Storm Holds Eastern Ontario In Its Beautiful But Deadly Grip," **The Record** (9 January 1998), p. A1.
61 Contenta, op. cit., p. A1.

treating for carbon monoxide poisoning 120 people "who ran generators, kerosene heaters and even charcoal grills in their homes to keep warm."[62]

Hospital medical services underwent a crisis during the protracted blackout when their emergency generators failed. For example, at Montreal's LeMoyne Hospital:

> *The generators broke down on the sixth day, and the staff instantly switched to flashlights. For two hours until the generators were repaired, the hospital lost the use of its life-support and monitoring equipment: Nurses pumped air by hand into the lungs of patients on respirators and manually took each patient's pulse and blood pressure every 15 minutes. Instead of one nurse for each six patients, a ratio of at least one-to-one was needed.*[63]

The blackout indirectly caused hundreds of deaths in Canada and the U.S., according to Great Ice Storm historian Jacques Leslie. Leslie criticizes the official death toll figures as too low:

> *The official de*ath toll was 45-28 fatalities in Canada, 17 in the U.S.—but those numbers understate *the ice storm's effects. Hundreds of ill and elderly people, weakened by extended stays in shelters where flu became epidemic, died weeks or months later, succumbing to ailments they might otherwise have overcome.*[64]

Over a year after the Great Ice Storm ended, according to Jaques Leslie, "The people who experienced it remain aware of one overriding lesson: Their dependence on electricity makes them more vulnerable than they'd ever imagined."[65] Mark Abley, author of **The Ice Storm**, makes a similar observation:

> *Huddling in school gyms, church halls, shopping malls, and other shelters, the evacuees didn't pray for a return of fine weather. They prayed for a return of power. The ice storm demonstrated not that we are prisoners of brutal weather, but that we are all now hostages to electricity."*[66]

Western Heat Wave (10 August 1996)

A heat wave, with near record high temperatures, blacked out large parts of nine western states on a torrid Saturday afternoon, August 10th, 1996. Near-record high temperatures covered most of the West at the time: for example, over 100 degrees in eastern Oregon and the San Joaquin Valley, 113 degrees in Red Bluff, and 104 degrees in Boise, Idaho.[67] Initial speculation that the blackout was sparked by a brushfire near Oregon was later discounted. According to

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62 Peter Pochna and Abby Zimet, "Facing Down An Ice Storm," **Portland Press Herald** (18 January 1998), p. 1A.
63 Leslie, op. cit., pp. 178, 180.
64 Ibid, pp. 122-123.
65 Ibid, p. 123.
66 Ibid.
67 Rich Connell, "Massive Power Outage Hits Seven Western States," **Los Angeles Times** (11 August 1996), p. 1.

Dulcy Mahar, spokeswoman for the Bonneville Power Administration, the blackout was caused by the heat wave:

> *Some of the lines sagged because of the heat. Some of those lines sagged down onto trees and then tripped off for safety reasons. The power that those lines were carrying was moved off to other lines and overloaded those, and then the safety devices tripped those lines off and you had the outages.*[68]

Although the blackout lasted less than 24 hours, it was "one of the largest power outages on record."[69] The blackout affected "an estimated 4 million people in nine states, trapping people in elevators, snarling traffic and generally causing widespread chaos."[70] The blackout caused problems that could have become a significant threat to life and society, had they been more protracted.

Water supplies were interrupted in some regions because electric pumps would not work. Arizona, New Mexico, Oregon, Nevada, Texas, and Idaho experienced blackout-induced disruption in water service during the heat wave. For example:

> *In Fresno, where most of the city receives water from wells powered by electric pumps, the city manager declared a local emergency. Only two of the city's 16 fire stations had water sources and most of the fire hydrants were out. The county and Air National Guard rushed in tankers to boost the Fire Department's capacity.*[71]

Air and ground transportation systems experienced significant disruptions because of the blackout. For example, at San Francisco International Airport, although an emergency generator powered the control tower, other systems—security, computers, elevators, and luggage carousels—would not work. Jetways could not be positioned at airplane doors. An estimated 6,000 passengers were stranded.[72] Incoming flights had to be diverted to San Jose and Oakland. Airport Spokesman Bob Schneider announced, "We are pretty much out of business."[73]

Signal lights failed, causing massive traffic jams in San Francisco and San Diego. "Traffic is a nightmare," declared San Francisco Police Department spokesman Bruce Metdors, "They're just backed up everywhere. It's gridlock."[74] San Francisco mass transit—electric trollies and BART metro trains—were stalled by the blackout.[75] "We're responding in what amounts to our earthquake mode," said Orange County Fire Captain Dan Young, "We certainly had an increase

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68 Tim Golden, "Power Failure in 6 Weeks Creates Havoc for the West," **New York Times** (12 August 1996), p. 13. See also Tina Griego, "Regulators Will Take Up Western Power Failures," **Albuquerque Tribune** (12 August 1996), p. A1.

69 Connell, op. cit., p. 1.

70 Robert Dintleman, "Western Power Failures Traced To Soaring Temperatures," **All Things Considered, National Public Radio** (11 August 1996), Transcript #2302-5.

71 Connell, op. cit., p. 1.

72 Ray Delgado, "Huge Blackout Hits West Coast," **San Francisco Examiner** (11 August 1996), p. A1.

73 Connell, op. cit., p. 1

74 Ibid.

75 Delgado, op. cit., p. A1.

in traffic collisions, since you've got thousands of signals with no control on them."[76] Gas pumps were out of order, stranding motorists who needed to refuel. "All the pumps run on electricity," explained one station attendant, "When you think about it, everything runs on electricity."[77]

"Even a few hours without electricity caused chaos," according to press reports:

> *Los Angeles police went on a citywide tactical alert as supervisors ordered some day shift officers to stay on duty into the night. Firefighters patrolled the city, responding to dozens of reports of stuck elevators. Department of Transportation crews checked on 4,000 intersections where the outage could have put traffic lights on the fritz. Blaring fire alarms and broken water lines added to the havoc.*[78]

Communications were disrupted by the blackout. "Radio stations reported power outages at locations throughout the midsection of California," according to press reports, "In San Francisco, TV stations KPIX and KQED were off-line for some time due to the outage."[79] Radio Station KNBR and the Canadian Broadcast Corporation went off the air.[80] Cable television networks crashed.[81]

Emergency medical services were disrupted by the blackout because "trauma rooms across the state [California] were cut off for hours from the radio that tells them an emergency is heading their way."[82] Fire crews equipped with portable power generators were sent to doctors' offices so the physicians could complete surgeries.[83] In Orange County, 200 fire units were dedicated to providing power to hospitals with emergency vehicles.[84]

The blackout disrupted control systems in some major industrial facilities. For example, the Chevron refinery in Richmond, California, "was unable to control flues due to the outage," releasing "huge clouds of black smoke."[85] The blackout caused power plants throughout the west—"including nuclear plants near Central California's Morro Bay and west of Phoenix"—to shut down.[86] The Diablo Canyon nuclear power plant, near San Luis Obispo, shut down, and required several days for technicians to complete safety checks before it could be started again.[87]

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76 Kim Boatman and Lori Aratani, "Millions Lose Power," **San Jose Mercury News** (11 August 1996), p. 1A.
77 Marilyn Kalfus, Ana Menendez, and Julio Laboy, "Blackout Brings Much Of O.C. To A Halt," **Orange County Register** (11 August 1996), p. A1.
78 Connell, op. cit., p. 1.
79 Delgado, op. cit., p. 1.
80 Boatman and Aratani, op. cit., p. A1.
81 Kalfus and et. al., op. cit., p. A1.
82 Ibid.
83 Douglas E. Beeman, "Hot West Goes Dim," **The Press Enterprise** (11 August 1996), p. A1.
84 Jim Hill, "West Coast Power Outage Easing In Some Locations," **Show, CNN** (10 August 1996), Transcript #1600-4.
85 Delgado, op. cit., p. 1.
86 Beeman, op. cit., p. A1.
87 Golden, op. cit., p. 13.

The Bonneville Power Administration told the press, "All of the utilities are relying on each other, and it has a cascading effect when one part experiences a major failure."[88]

Hurricane Andrew (August 1992)

Hurricane Andrew struck southern Florida on August 24, 1992 and reached the coast of Louisiana on August 26, two days later. Andrew has been described by some experts as the worst natural disaster in U.S. history. [89] Andrew laid waste to 165 square miles in South Florida, destroying some 100,000 homes in Florida and Louisiana, and leaving more than 3.3 million homes and businesses without electricity.[90]

Federal and state officials were at first unaware of the magnitude of the disaster and slow to react. Three days into the crisis, Kate Hale, the Director of Dade County's Office of Emergency Management called a press conference to demand of state and federal authorities, "Where the hell is the cavalry on this one? We need food. We need water. We need people. For God's sake, where are they?"[91]

By the end of the first week, President Bush had ordered 14,400 troops into the Florida disaster area "with mobile kitchens, tents, electrical generators, water and blankets….Even those lucky enough to have homes may not have electricity for more than a month."[92]

Andrew's aftermath posed an immediate threat to life in South Florida because of damage to the infrastructures for water and food. A widespread electrical blackout prevented pumps from working, so there was no running water.[93] Most grocery stores had been destroyed. Massive traffic jams, caused in part by non-functioning signal and street lights, prevented the surviving supermarkets from being re-supplied. To meet the crisis, the Army Corps of Engineers distributed more than 200,000 gallons of water and the Department of Agriculture gave out tons of surplus food.[94] Nonetheless, two weeks after the hurricane, food was still not reaching many victims. On September 7, fifteen days after Andrew struck, reporters witnessed the following scene:

> *In the ruins, Charlie Myers, 65, stood holding a peach and a loaf of bread. "This is all I have left, he said. What plans did he have? "Survive buddy."*[95]

Andrew's blackout of the power grid made the crisis over water, food, and shelter worse by severing communications between relief workers and victims. Without power, there was an

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88 Delgado, op. cit., p. 1.

89 "Mother Nature's Angriest Child," **Time** (7 September 1992), p. 15.

90 Tom Mathews, Peter Katel, Todd Barrett, Douglas Waller, Clara Bingham, Melinda Liu, Steven Waldman, and Ginny Carrol, "What Went Wrong," **Newsweek** (7 September 1992), p. 23.

91 Ibid.

92 "Mother Nature's Angriest Child," op. cit., p. 16.

93 William Booth and Mary Jordan, "Hurricane Rips Miami Area, Aims at Gulf States," **Washington Post** (25 August 1992), p. A7.

94 Mathews and et. al., op. cit., p. 27.

95 Ibid.

almost complete collapse of communications—no phones, radio or television.[96] "Without electricity to power radio and television sets, mass communication remains difficult or impossible," according to authorities and press reports.[97] Consequently, people were unaware of relief efforts or of where to go for help. For example, although the U.S. Marines erected "tent cities" able to accommodate thousands of homeless hurricane victims, many did not know of this refuge: "Many people in the vast storm-stricken area, even those who live within easy walking distance of the sprawling encampment, said they were not aware of the tents' existence."[98] Unable to communicate where victims could get water, relief workers stacked "pyramids of bottled water…on street corners, free for the taking."[99]

The blackout of power and communications, according to press reports, imbued "South Florida with an end-of-the world aura":

> *Hundreds of thousands of people found themselves in a Stone Age existence, left to pursue hunting and gathering, forced to forage for food and water. Because many people in the devastated areas had no radios or batteries, the location of food distribution sites has been a mystery….Each time word spread about establishment of a new relief outlet, people suddenly would swarm forward on foot, and National Guard troops often had to be summoned to keep order. The hurricane robbed steamy South Florida of the two amenities deemed essential to life here: air conditioning and ice cubes. "We can't stand this heat any longer," said Rita Larraz, whose house in South Dade County was spared but who, like 750,000 customers here, still had no electricity, and therefore no air conditioning in the 90-plus degree heat and humidity…"The heat is killing us."*[100]

The blackout crippled the transportation infrastructure, further impeding relief efforts. "More than 5,000 traffic lights are on the blink…," according to press reports. Consequently, "Traffic was snarled for miles. The simplest chore, indeed almost everything, seemed to take forever."[101]

Andrew's blackout of the power grid contributed significantly to societal anarchy in South Florida. With the blackout induced collapse of communications there was no way for survivors of Andrew to report crimes in progress. An orgy of looting provoked vigilantism. Unable to rely on the police, individuals armed themselves to protect their homes and remaining possessions.

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96 One report indicates the phone system continued to operate or experienced only partial failure. See John Mintz, "Phones Withstand Hurricane's Fury," **Washington Post** (26 August 1992), p. F1. For a different view see Booth and Jordan, op. cit. (25 August 1992), p. A7.

97 Laurie Goodstein and William Booth, "Marines Ready Tent Cities in South Florida," **Washington Post** (1 September 1992), p. A1.

98 Ibid.

99 Ibid.

100 William Booth, "Hurricane's Fury Left 165 Square Miles Pounded Into the Ground," **Washington Post** (30 August 1992), p. A1.

101 Goodstein and Booth, op. cit., p. A1.

"Andrew had made one zone of society come unglued," according to **Newsweek**, "Disasters penetrate like lasers, revealing weaknesses beneath the smooth surfaces of a community."[102] Lack of streetlights encouraged "thieves…to take advantage of a general feeling of lawlessness, particularly before federal troops began arriving":

> *At night, in darkened streets cordoned by National Guard troops enforcing a curfew, machine-gun fire has been heard. Spray-painted on the side of a house in Perrine was: "I'm armed and dangerous! Looters shot on sight!" "Everyone is armed, everyone is walking around with guns," said Navy physician Sharon Wood, who worked at a mobile hospital in Homestead, where workers refused to dispense calming drugs such as valium for fear that word might get out and the hospital might be robbed. In Kendall, senior citizens sleep at night with revolvers by their sides….Miami and its surrounding municipalities, which have a long history of racial and ethnic tension, were considered a tinderbox.*[103]

Some 3,300 National Guard troops enforced a dusk-to-dawn curfew, when looting was worst, under cover of darkness. More than 200 people were arrested for looting or violating the curfew.[104] However, some efforts to restore law and order impeded relief efforts:

> *Roadblocks set up to stop looters continued to hamper delivery of emergency food supplies. Truckers with emergency food aid were forced to wait for police escorts after reports that some drivers had been shot and beaten by thugs. State troopers thwarted the progress of some private help when they began stopping all trucks entering the state, demanding that the drivers show that they and their cargo had been officially requested and that they were from a recognizable organization.*[105]

Ultimately, some 16,000 federal troops from every branch of the armed forces turned the lights back on and restored order to South Florida.[106]

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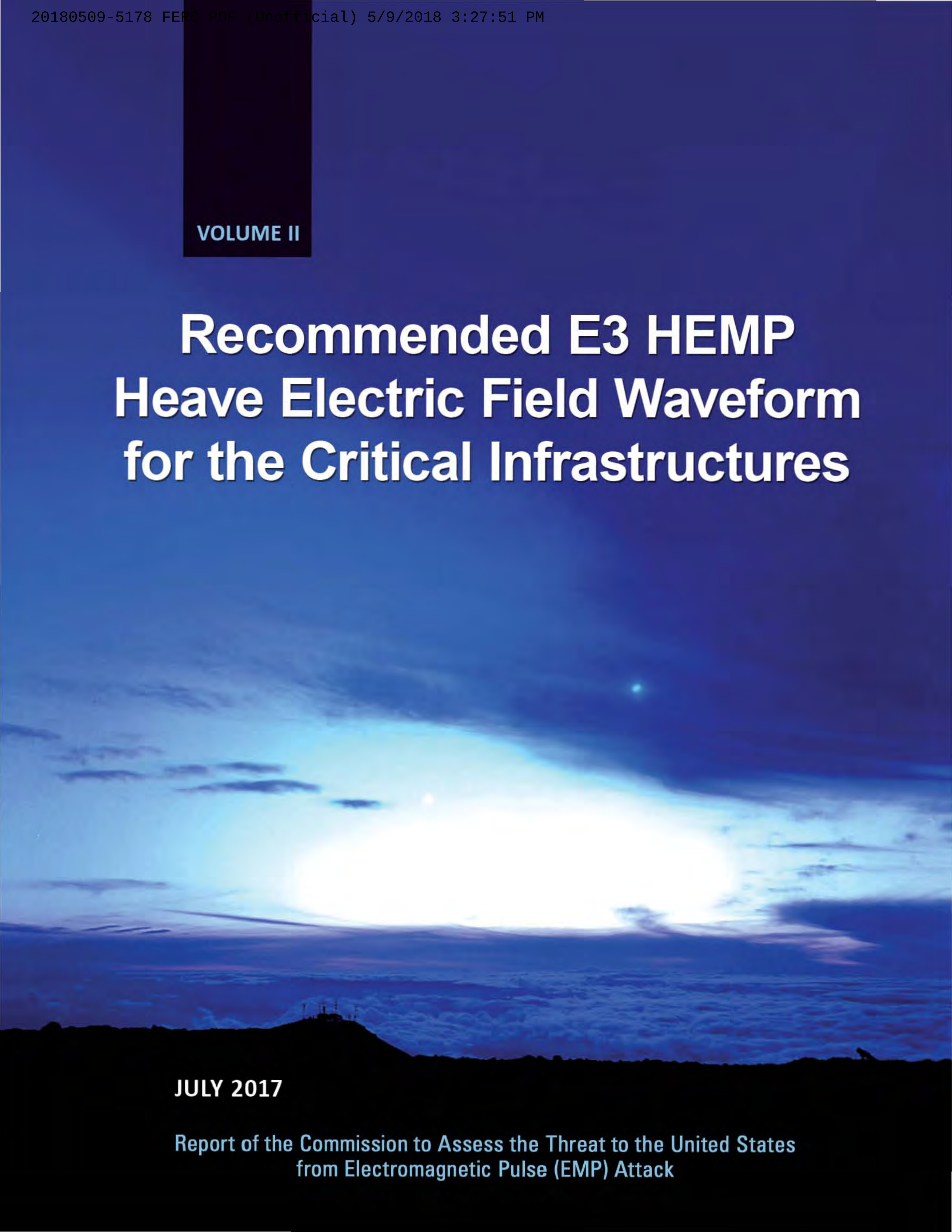
102 Mathews and et. al., op. cit., p. 24.
103 Booth, op. cit., p. A18.
104 William Booth and Mary Jordan, "Painful Awakening in South Florida," **Washington Post** (26 August 1992), p. A27.
105 Mary Jordan, "President Orders Military to Aid Florida," **Washington Post** (28 August 1992), p. A14.
106 Rick Gore, "Andrew Aftermath," **National Geographic** (April 1993), p. 20.



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

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.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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

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.

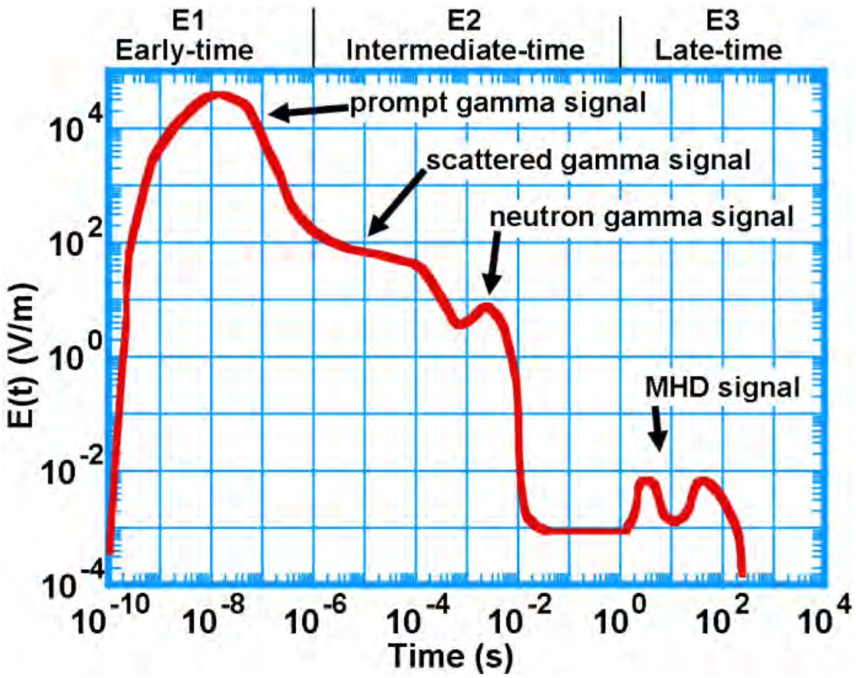

Figure 1 Parts of HEMP. E3 HEMP heave is roughly described by the second peak in the MHD signal. [SOURCE: Meta R-321]

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.

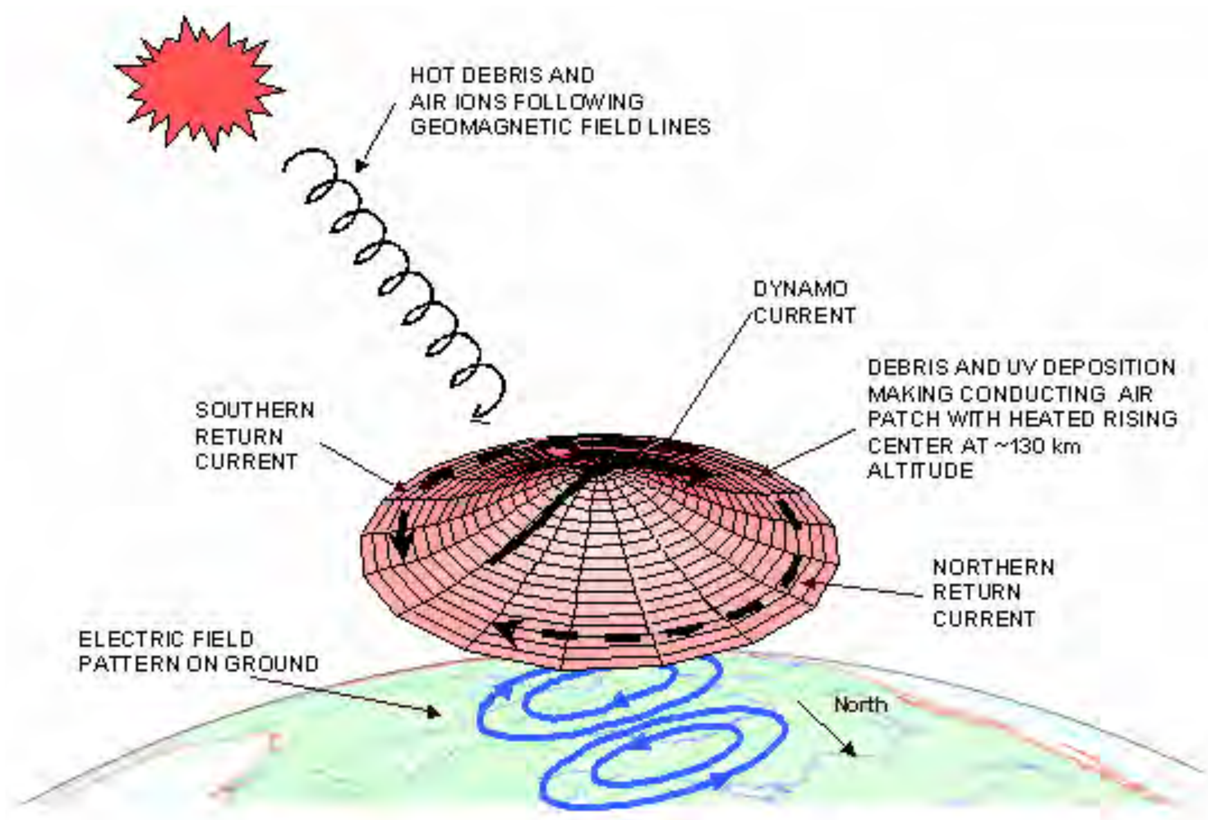

Figure 2 Diagram of the E3 HEMP heave effect. [SOURCE: Meta R-321]

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

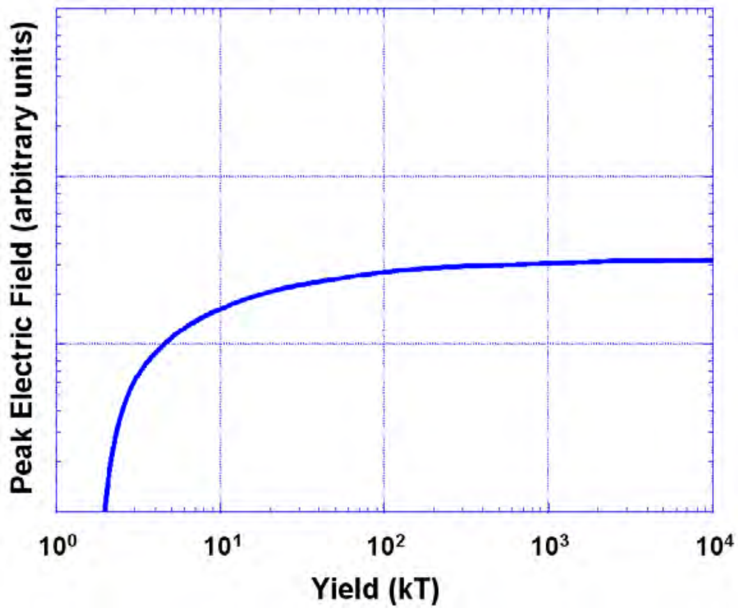

Figure 3 Sample normalized yield variation for maximum E field for heave for burst heights between 130 and 170 km and for a fixed Earth conductivity profile. [SOURCE: Meta R-321].

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

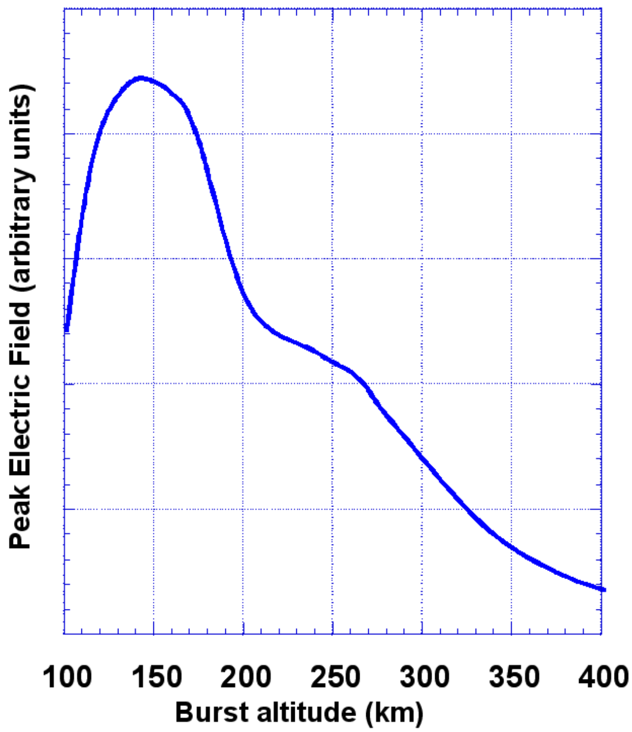

Figure 4 Sample normalized HOB variation for maximum peak E field for heave for an intermediate yield weapon and for a fixed Earth conductivity profile. [SOURCE: Meta R-321].

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.

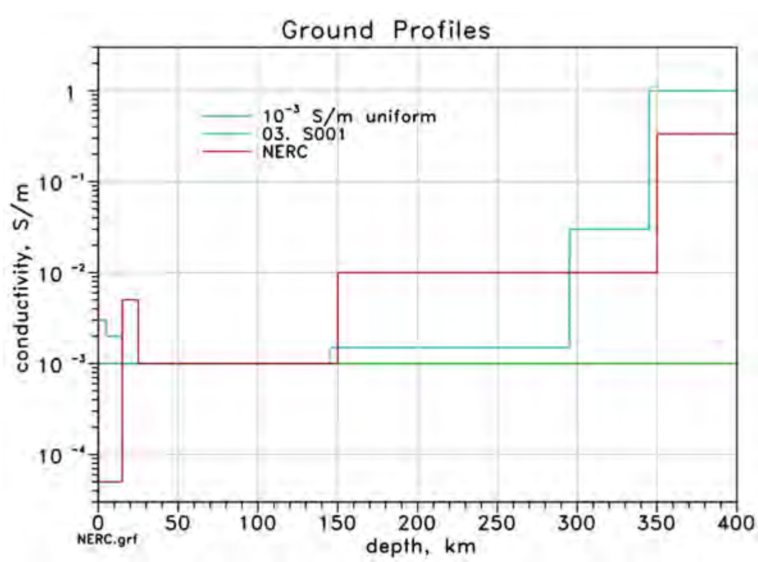

Figure 5 Ground conductivity depth profile for three ground profiles.

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.

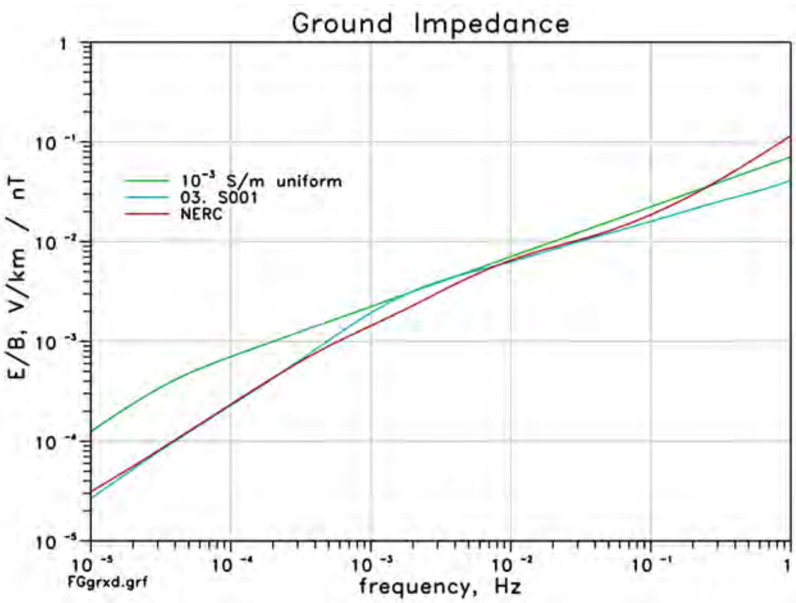

Figure 6 Ground profile B-to-E conversion in the frequency domain for three cases.

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.

[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.

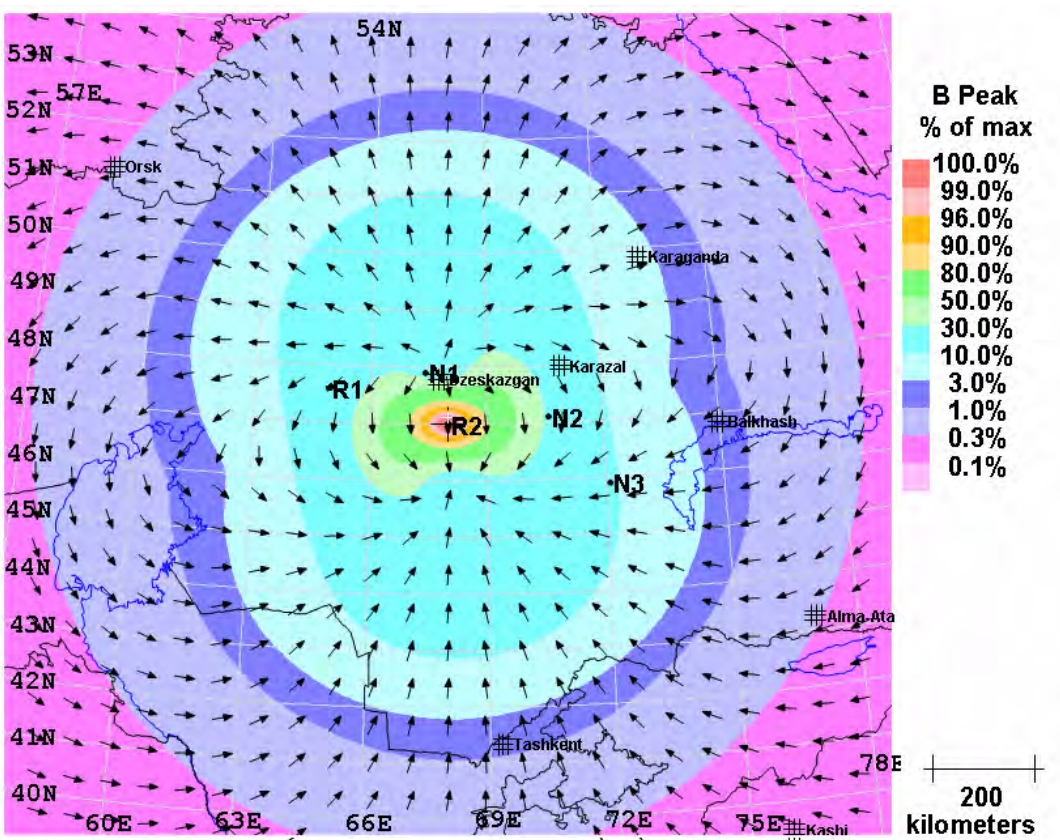

Figure 7 Simulation of the Soviet tests showing B field peaks and field directions,150 km test (R2).

[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.

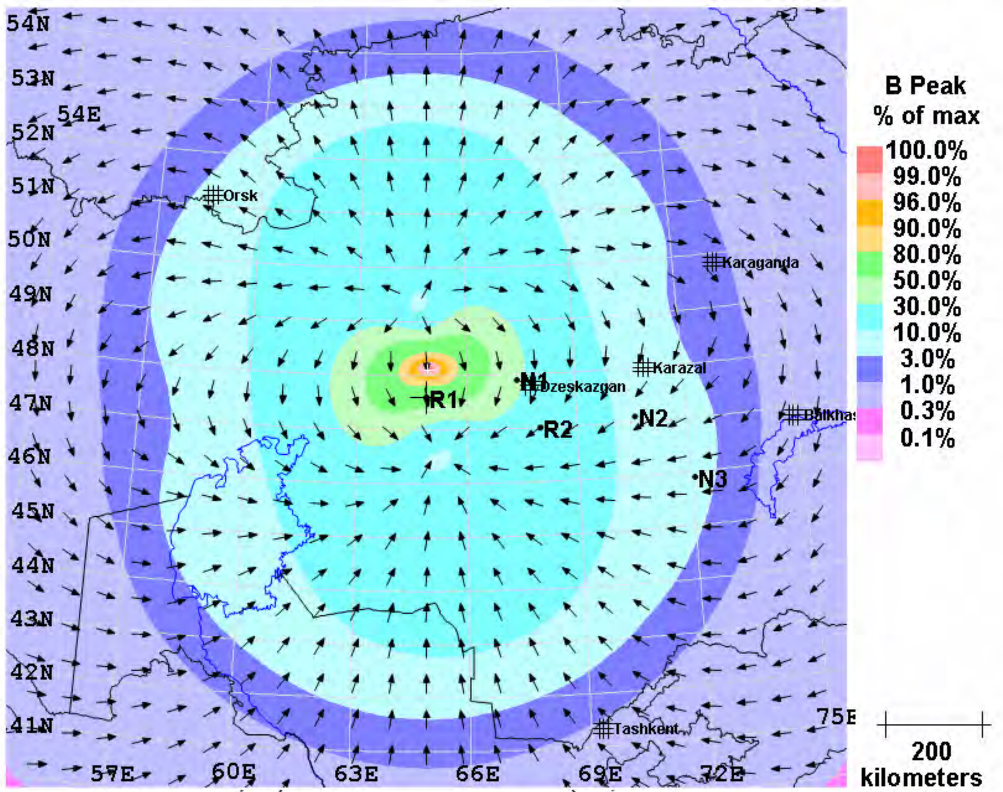

Figure 8 Simulation of the Soviet tests showing B field peaks and field directions, 300 km test (R1).

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.

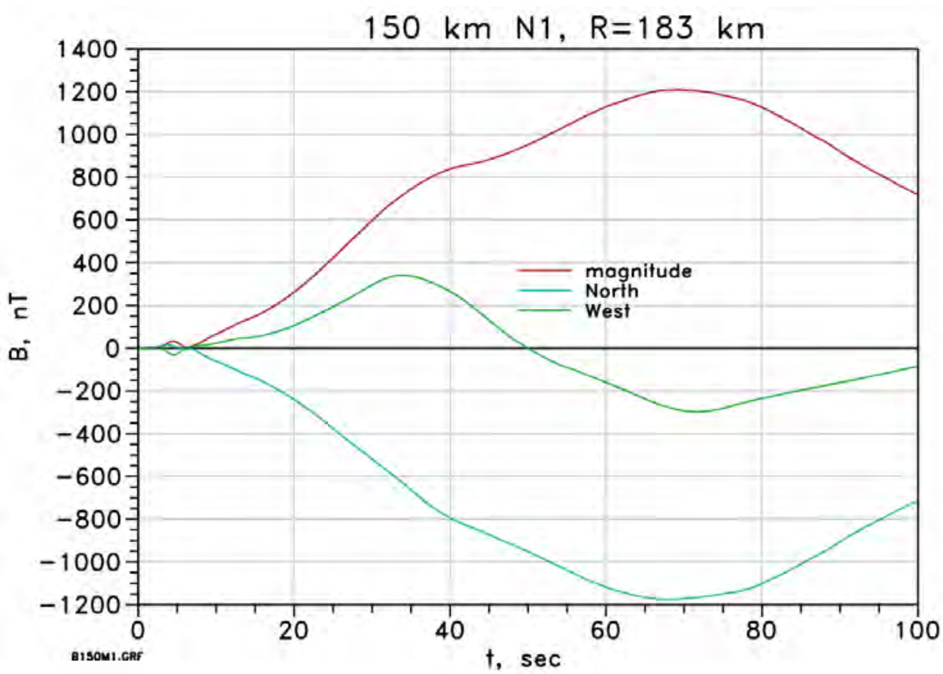

Figure 9 Measured B fields at N1, 150 km test.

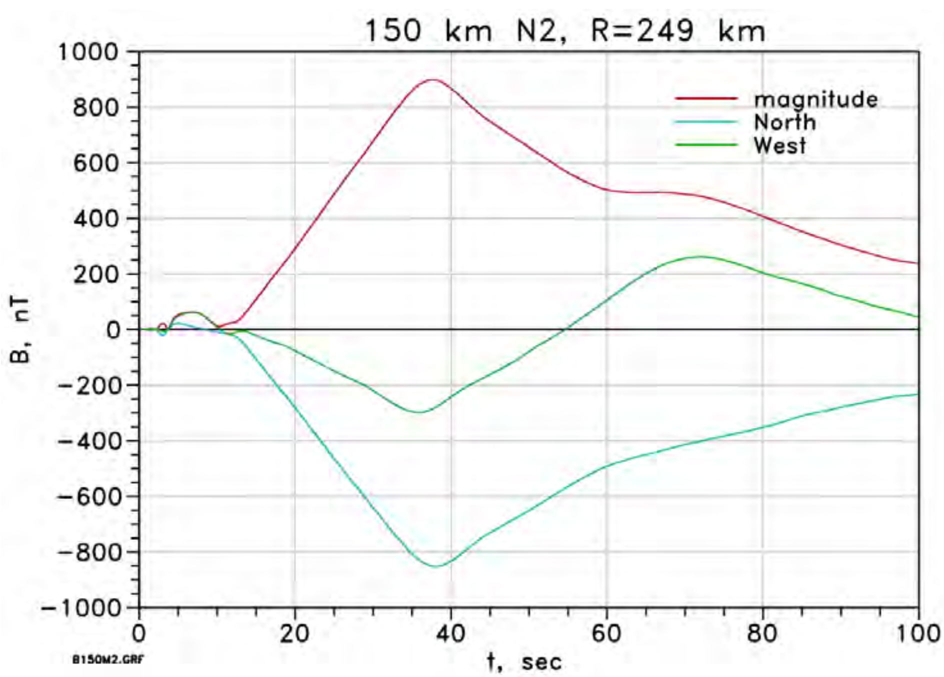

Figure 10 Measured B fields at N2, 150 km test.

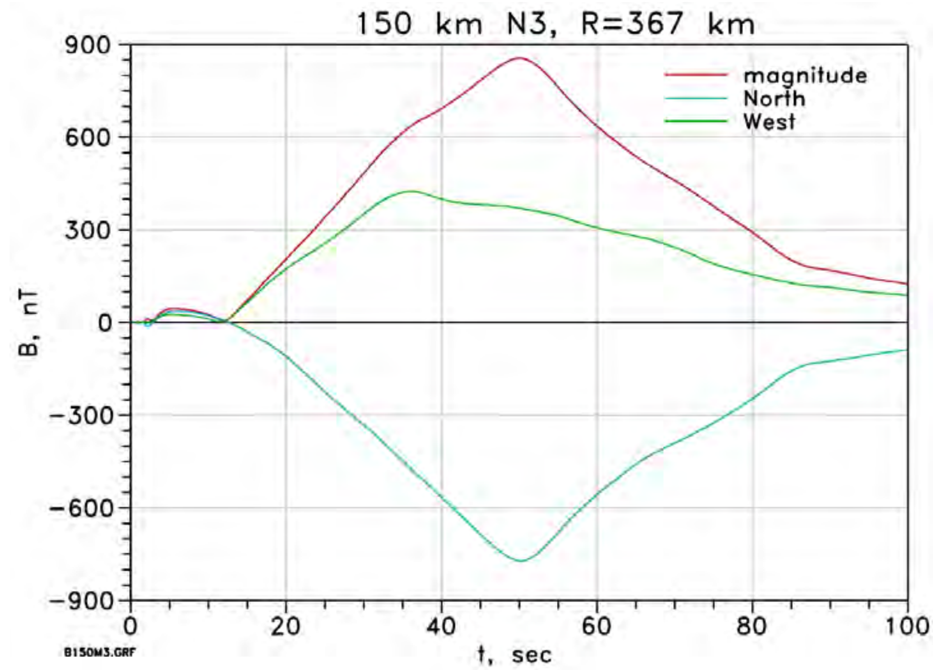

Figure 11 Measured B fields at N3, 150 km test.

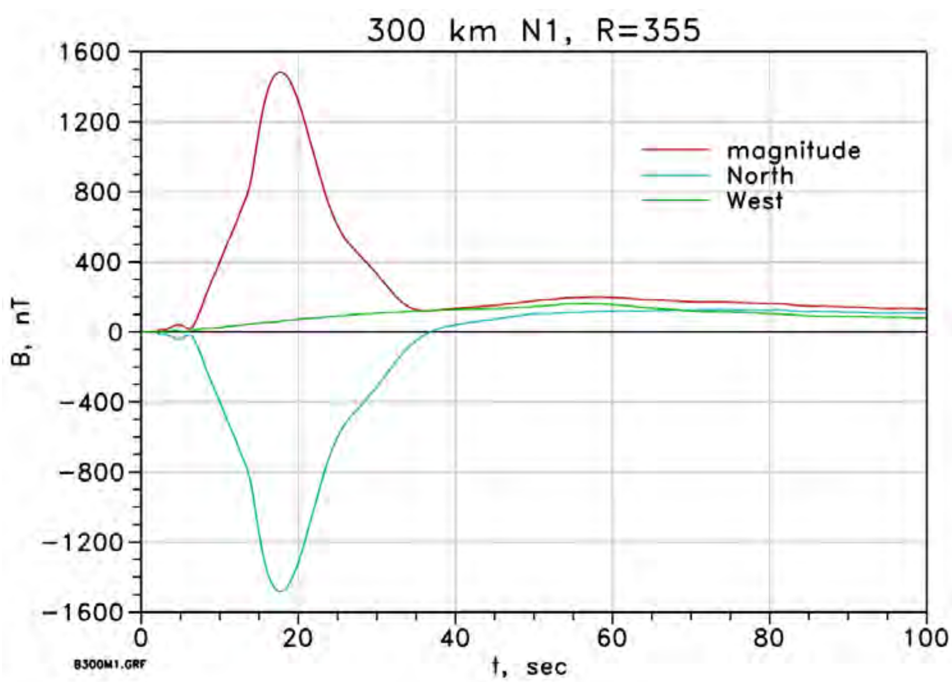

Figure 12 Measured B fields at N1, 300 km test.

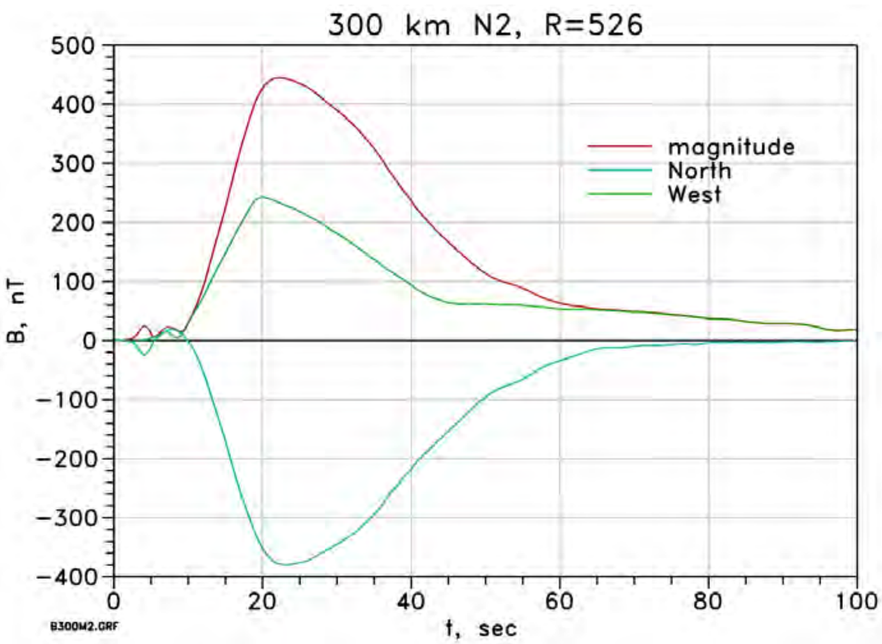

Figure 13 Measured B fields at N2, 300 km test.

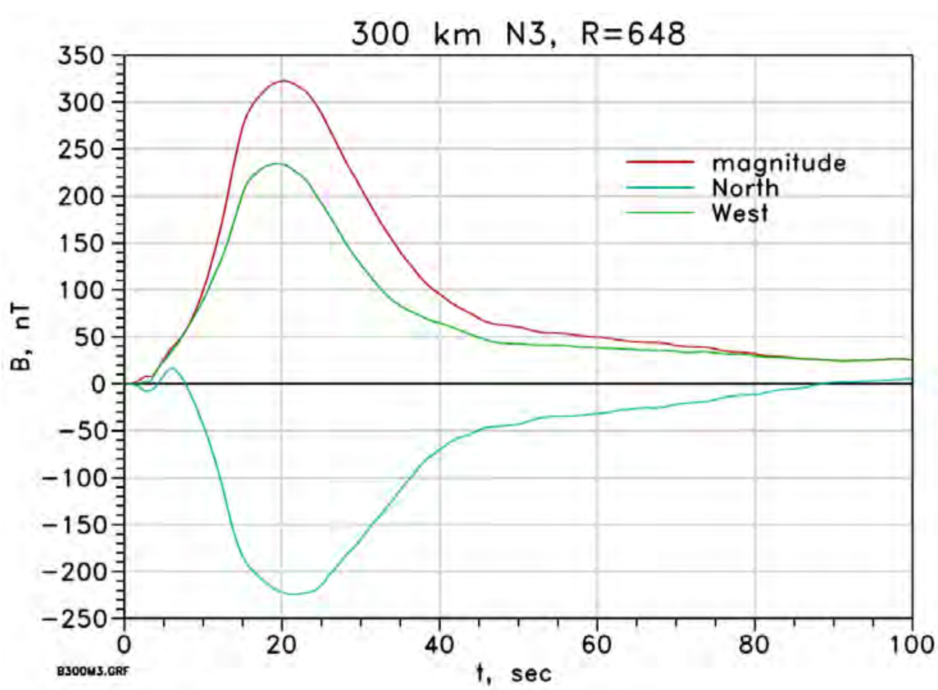

Figure 14 Measured B fields at N3, 300 km test.

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

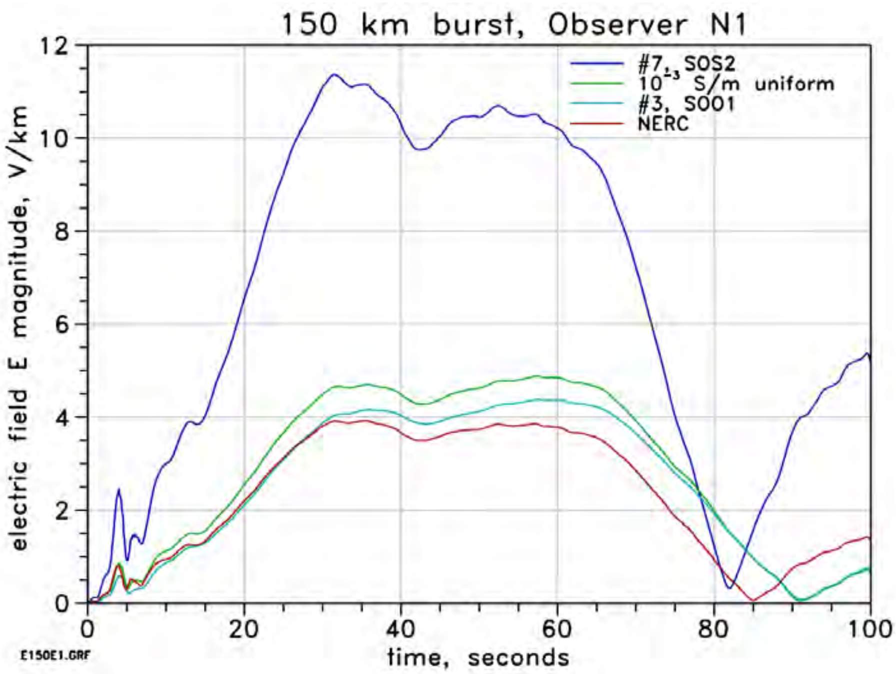

Figure 15 E field amplitudes for four ground profiles, at N1, 150 km test.

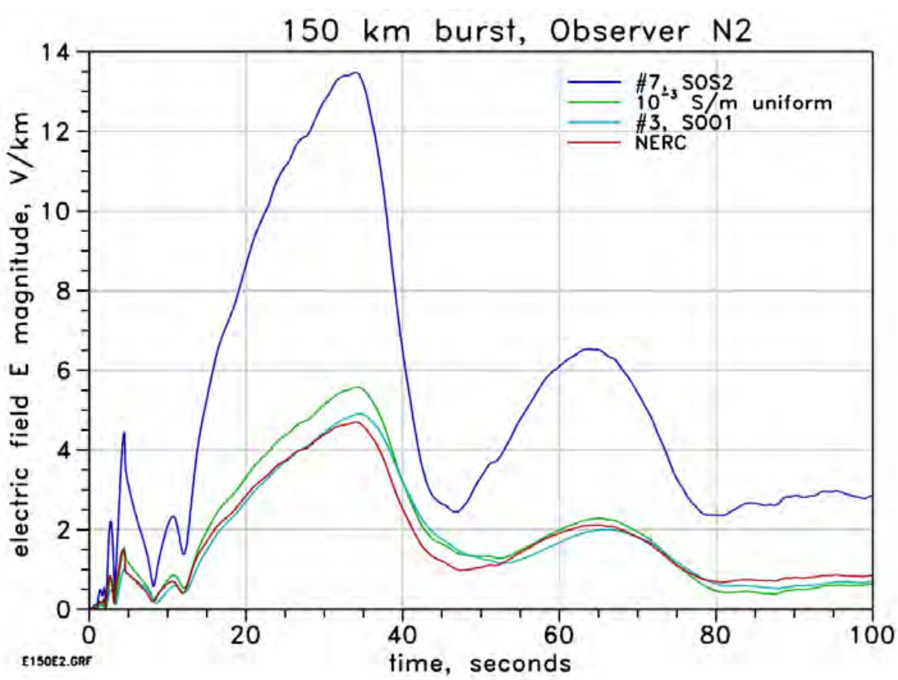

Figure 16 E field amplitudes for four ground profiles, at N2, 150 km test.

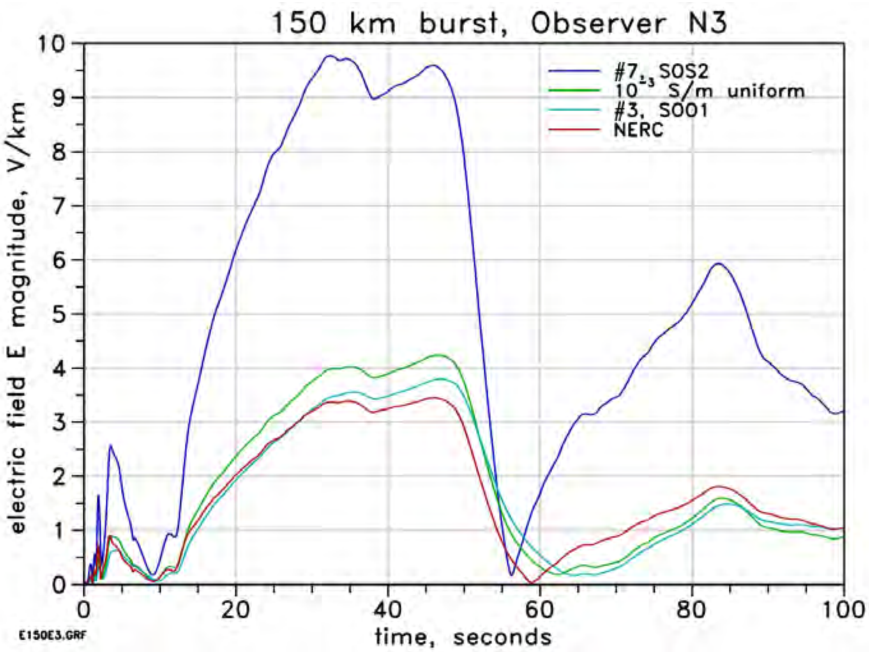

Figure 17 E field amplitudes for four ground profiles, at N3, 150 km test.

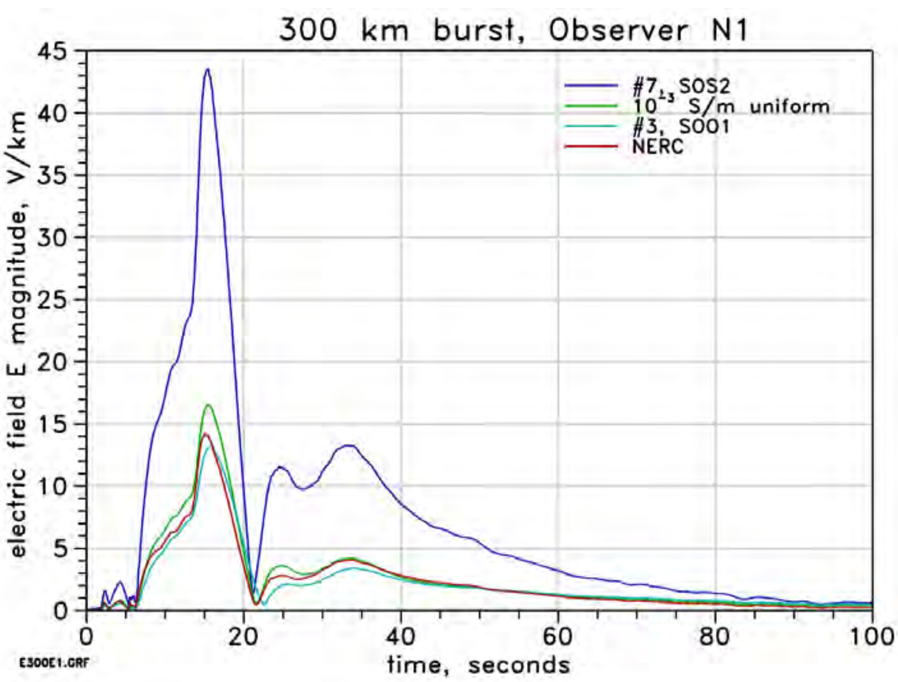

Figure 18 E field amplitudes for four ground profiles, at N1, 300 km test.

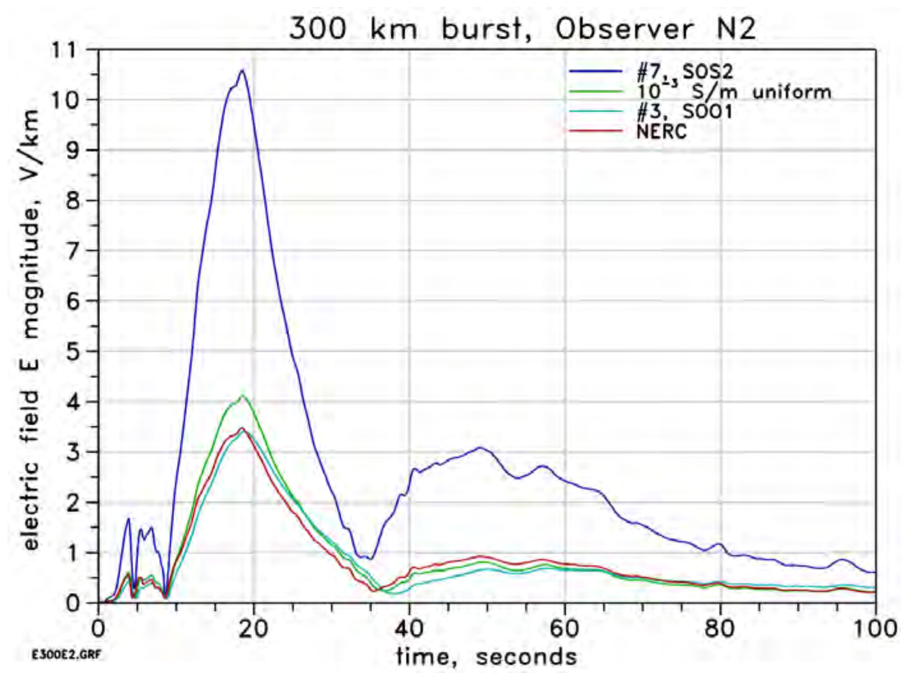

Figure 19 E field amplitudes for four ground profiles, at N2, 300 km test.

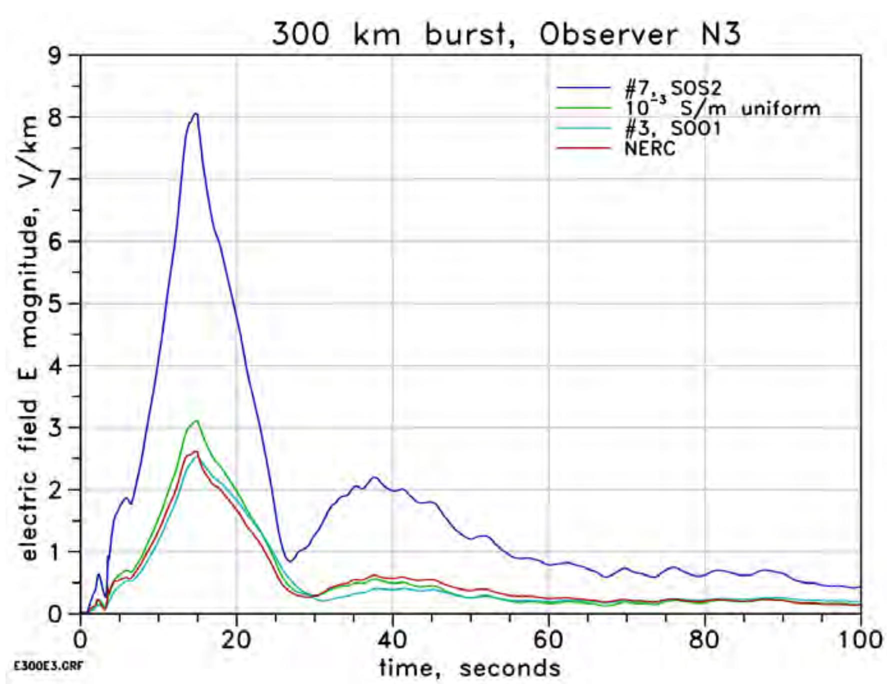

Figure 20 E field amplitudes for four ground profiles, at N3, 300 km test.

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^{o} N
300 km: 46.13^{o} 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^{o}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^{o}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^{o}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.

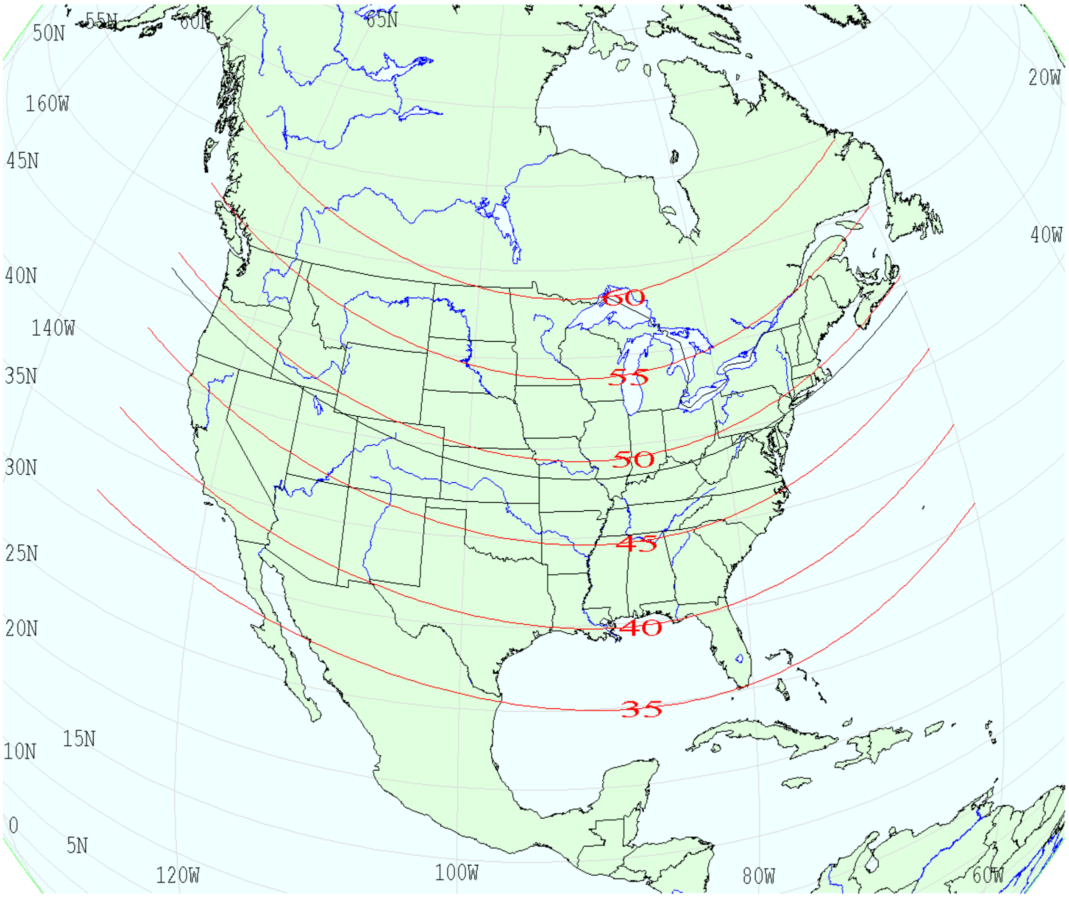

Figure 21 Geomagnetic latitude variation, for a 150 km burst, over the U.S. The black line is at 48.92°, which is the computed geomagnetic latitude for the 150 km Soviet test.

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						
			Alaska, 65° N		U.S., 35° N		Hawaii, 22° N	
		Soviet, B, nT	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.

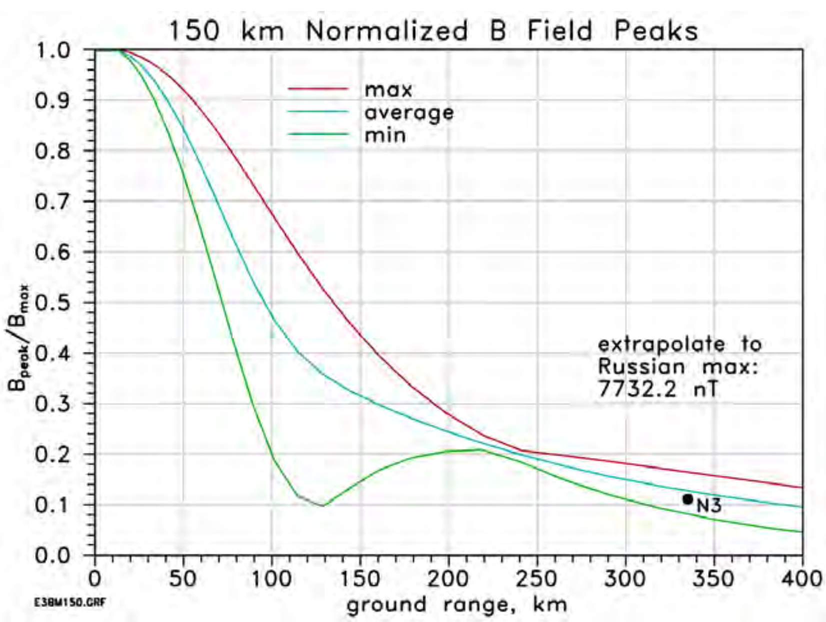

Figure 22 Normalized simulated B field peaks versus ground range for the 150 km test. The black dot

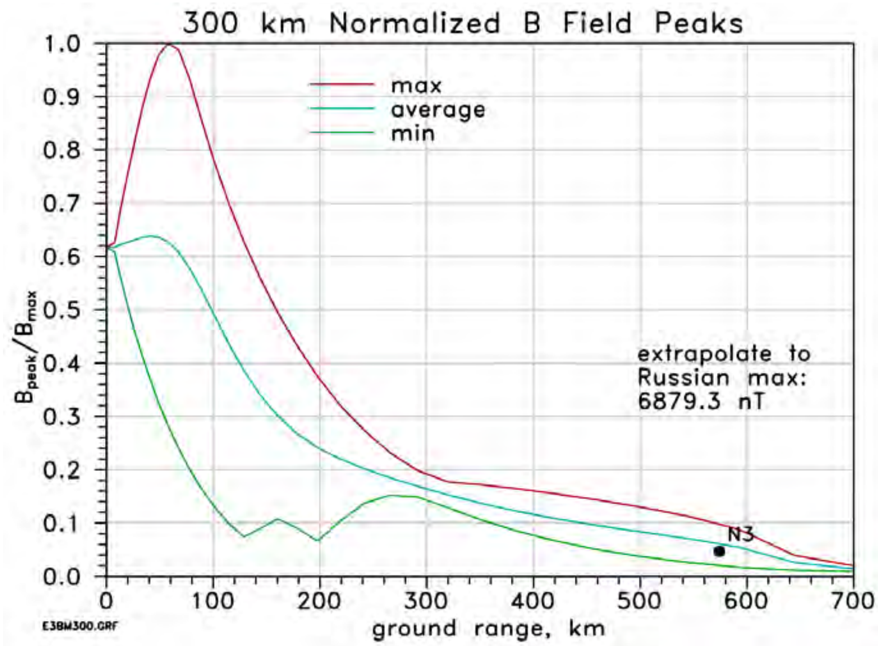

Figure 23 Normalized simulated B field peaks versus ground range for the 300 km test. The black dot shows the simulated results for the N3 point.

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

Case	Soviet Measurements		Latitude Scaling, E, V/km		
	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

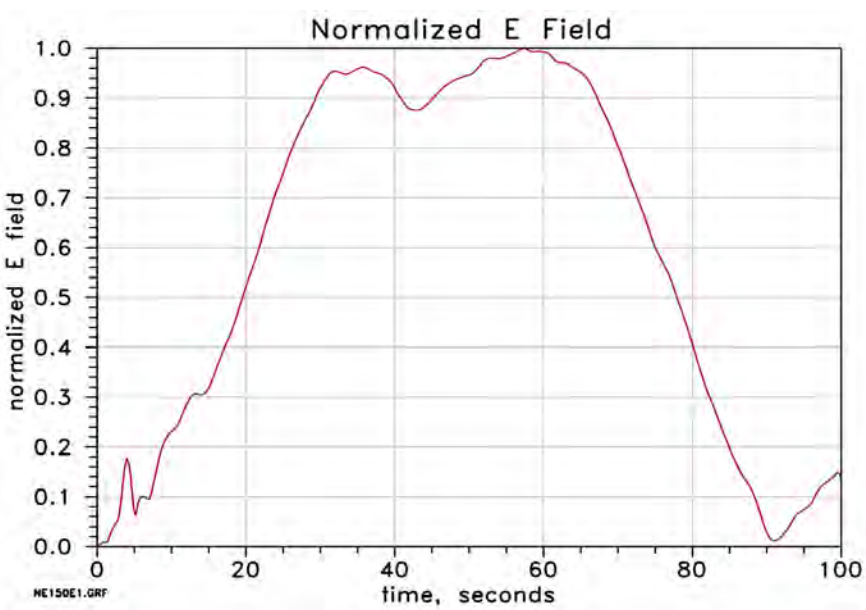

Figure 24 E field waveform shape, using the measured N1 waveform from the 150 km burst height

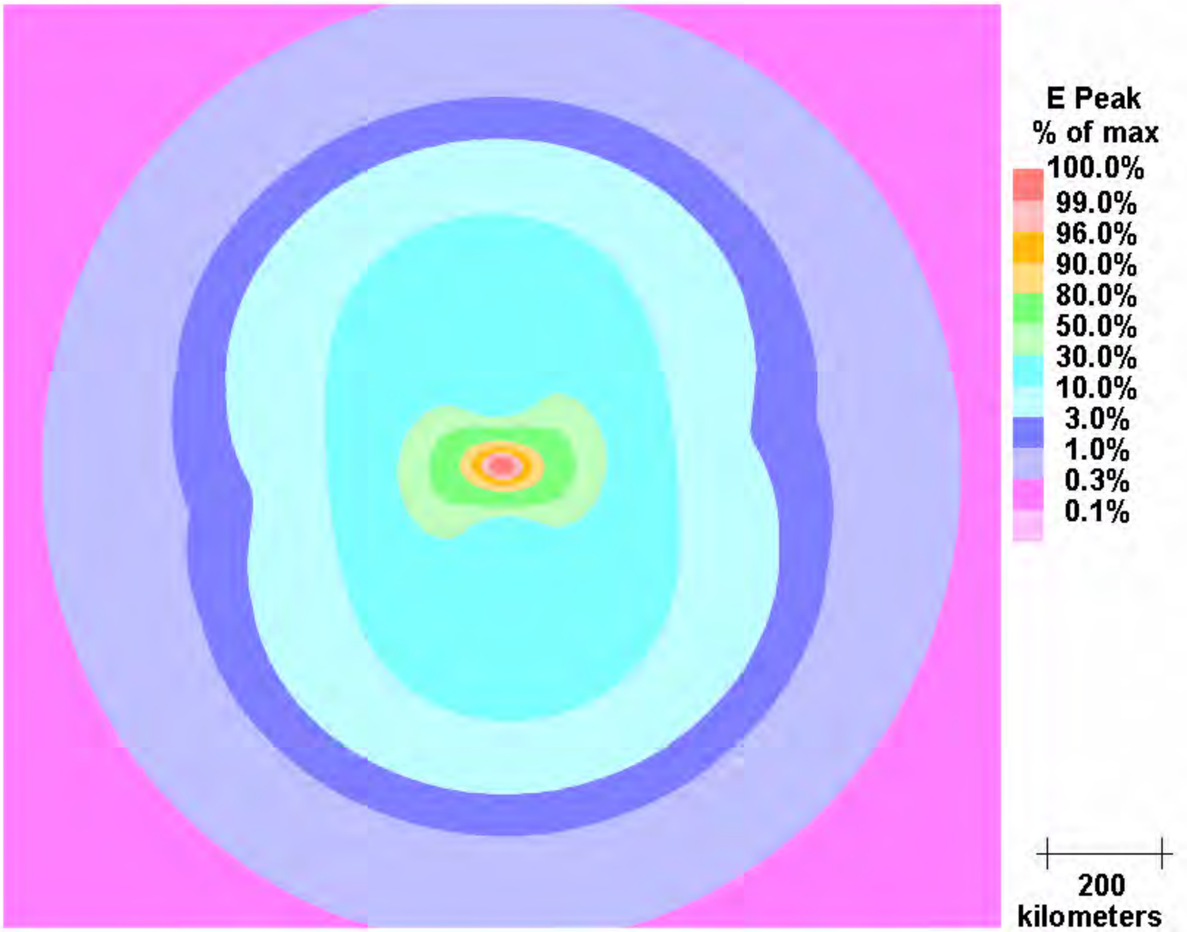

Figure 25 Normalized E peak contour pattern from the 150 km burst case

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.

Document Content(s)