The Severe Electromagnetic Threats to the Electric Power System (HEMP, IEMI and Geomagnetic Storms)

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Outline of Talk

- Introduction to terminology
- Overview of High-altitude Electromagnetic Pulse (HEMP)
- Overview of Intentional Electromagnetic Interference (IEMI)
- Overview of severe geomagnetic storms
- Protection issues and standards

Terminology

Background

- We live with electromagnetic (EM) environments every day
  - — Over the air radio (AM, FM, satellite)
  - — Mobile phones, WIFI, etc.
- While these are beneficial services, the levels of electromagnetic fields near these transmitters can be high
  - — Modern digital electronics cannot tolerate high level radiated or conducted electromagnetic threats without some protection
  - — Due mainly to their operation with gigahertz microprocessors
- Digital electronics are now part of our critical infrastructures including
  - — The electric power system (the "keystone")
  - — Communications, financial, transportation, etc.
- In the past high power EM threats were "provided" only by lightning, ESD and radar
- This presentation focuses on the "triple threats" of HEMP, IEMI and extreme geomagnetic storms

Terminology - 1

- Electromagnetic Pulse (EMP)
  - Used for over 40 years to describe the electromagnetic signals emitted from a nuclear detonation at any burst altitude
  - The military has defined HEMP, SREMP, SGEMP, IEMP, etc.
- High-altitude electromagnetic pulse (HEMP)
  - Used for over 40 years to describe the electromagnetic signals emitted from a nuclear detonation above ~30 km
  - Of biggest concern due to the fact that the HEMP fields are able to cover a continental region from 1 or 2 bursts
- In recent years, popular press articles have started to refer to all transient electromagnetic threats as EMPs
  - EMP bombs (non-nuclear, but usually explosive)
  - EM weapons (non-explosive, can fire many times)
  - Even geomagnetic storms

Terminology - 2

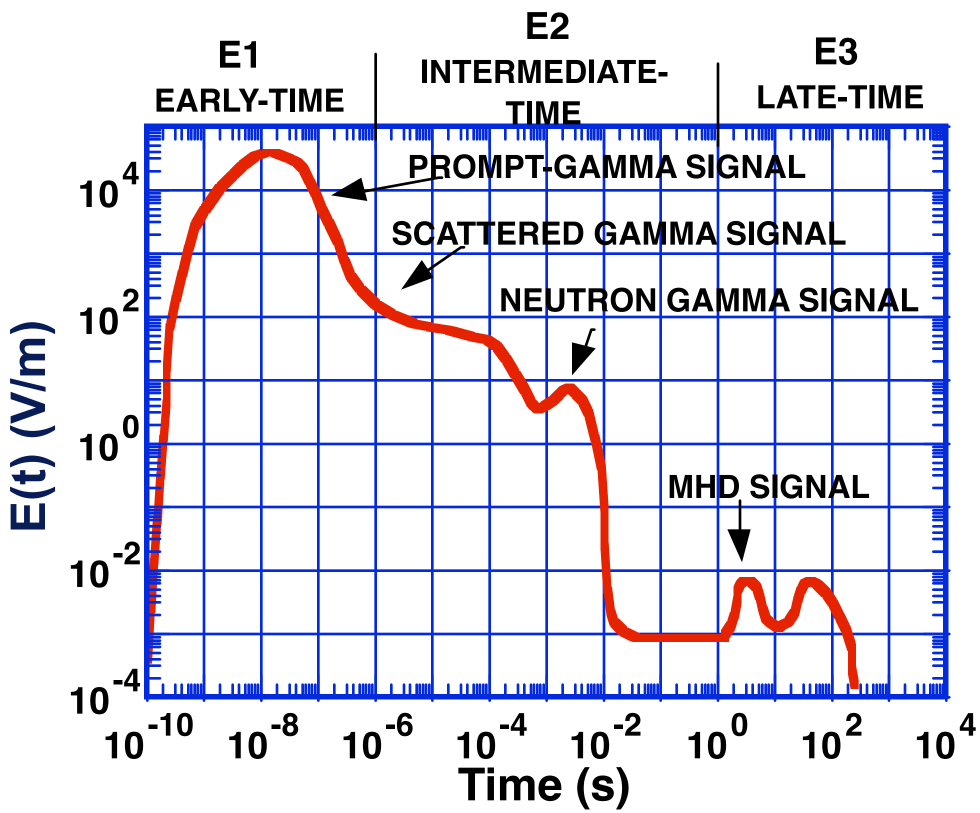
- To avoid confusion, formal definitions (IEC and IEEE) are used in this presentation

- In this presentation we will discuss three extreme electromagnetic (EM) threats to the commercial power system
  - HEMP (high altitude electromagnetic pulse) from a nuclear detonation in space
  - Intentional electromagnetic interference (IEMI) which is caused by the use of electromagnetic weapons by criminals and terrorists
  - Extreme geomagnetic storms on Earth (from solar activity)

- After discussion of each of the threats, some information regarding the susceptibility of the power system and its protection will be presented

Overview of HEMP

HEMP Environment Terminology



NOTE: E1 AND E2-GAMMA ARE INCIDENT FIELDS, E2-NEUTRON AND E3 CONSIDER THE PRESENCE OF THE GROUND

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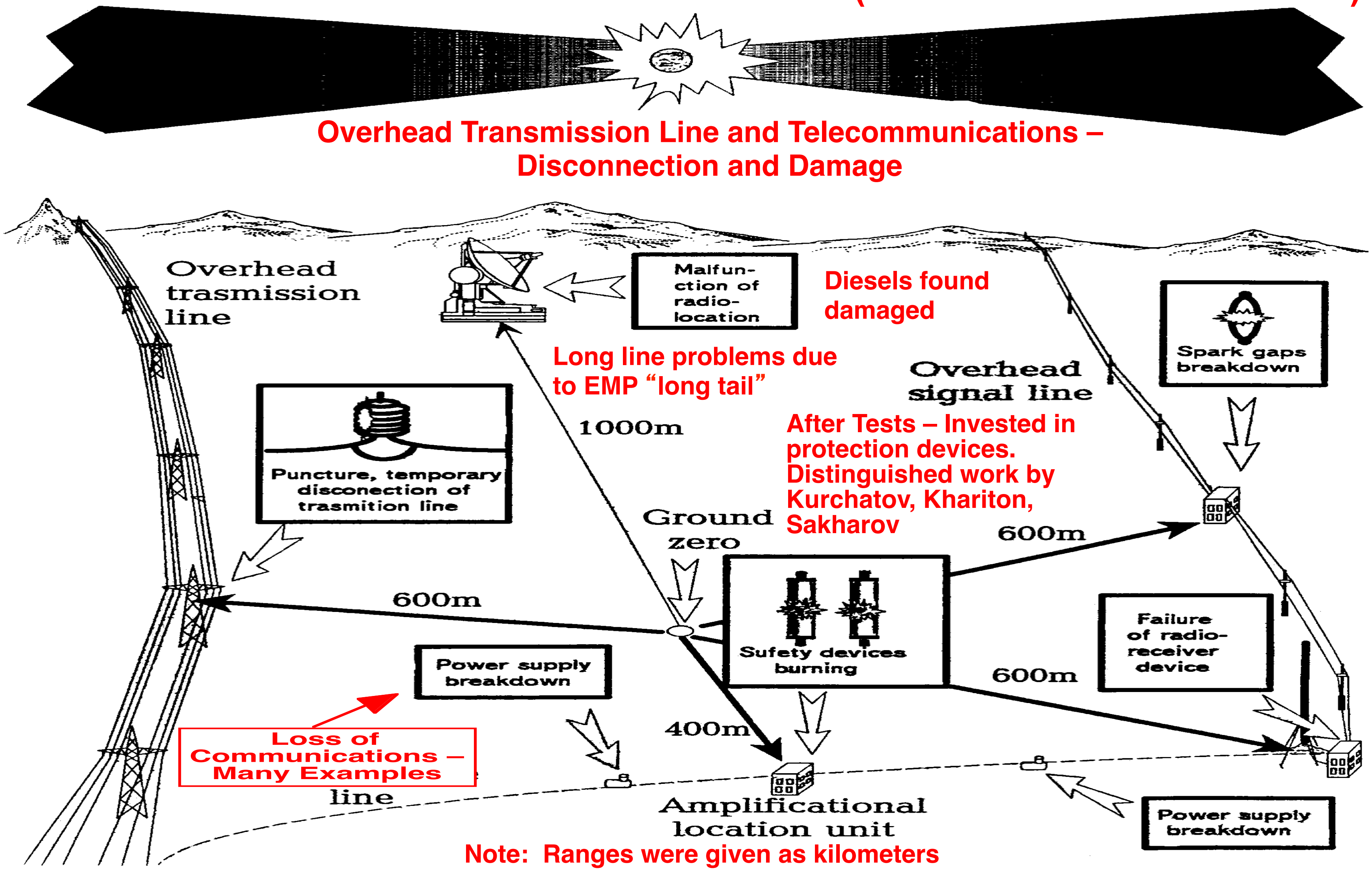
HEMP Threat: Historical Evidence (U.S.)

- STARFISH event, July 9, 1962
  - — Rocket launch from Johnston Is.
  - — 1.4 MT, 400 km HOB
  - — 1400 km from Honolulu
- HEMP effects observed in Hawaii
  - — Coupling to Hawaiian electric light grid turns off some nighttime lights in Honolulu
  - — Kauai telecom microwave outage
  - — Other nuisance effects (alarms)
- Collateral effect: Sky swept clean of all commercial satellites within six months (not HEMP or SGEMP)

Ref: EMP Commission (note Moon, plus “auroral” display)

HIGH ALTITUDE ELECTROMAGNETIC PULSE EFFECT (Kazakhstan - October 1962)



Note: Red text based on Prof. Loborev's spoken words in June 1994 as documented by Radasky

Ref: Prof. Loborev, EUROEM Bordeaux, 1994

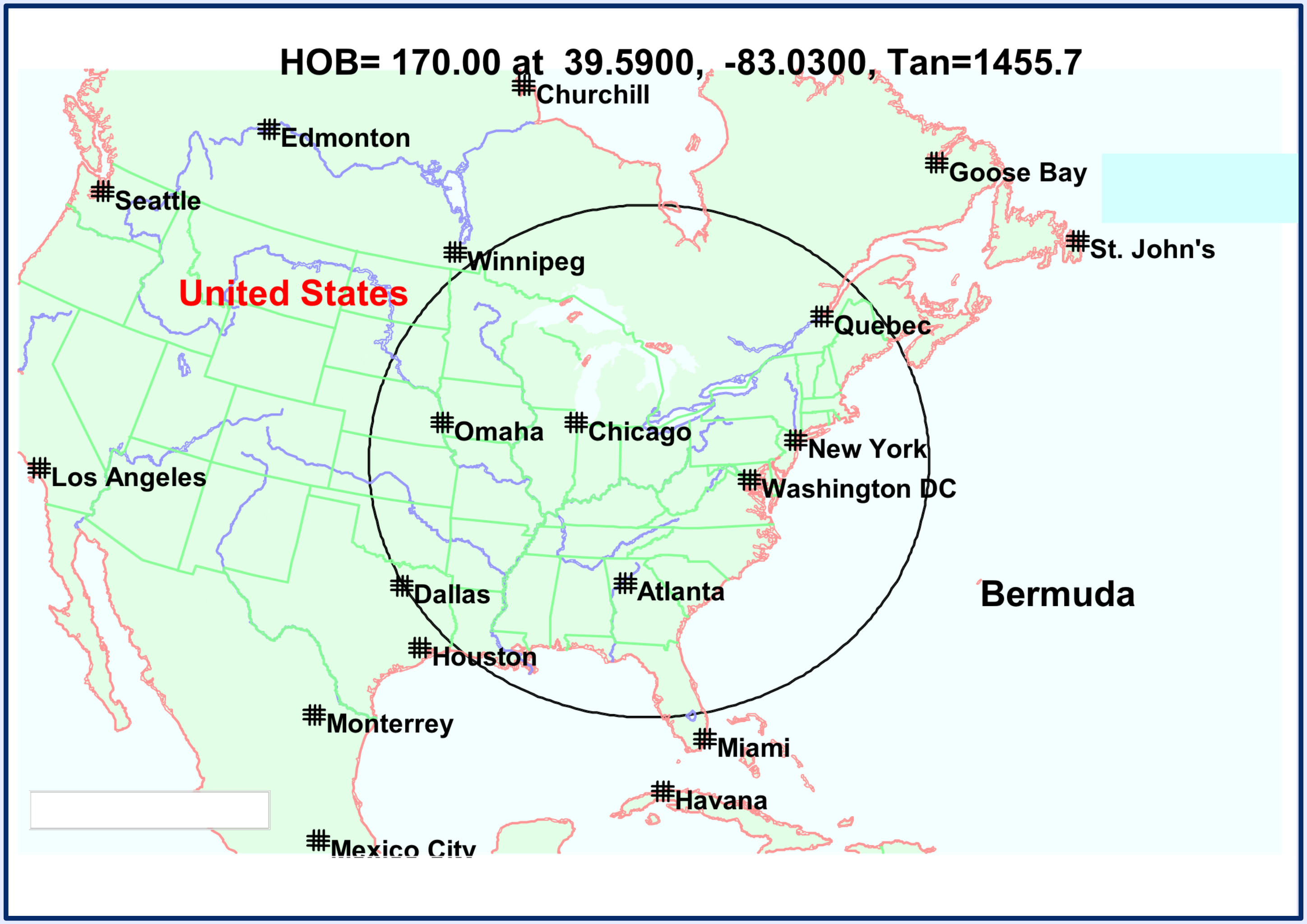
Metatech Power System Analysis for the EMP Commission

- Metatech performed an E1 HEMP assessment of the U.S. power grid in 2003/2004 for the EMP Commission
  - Studies focused on distribution line insulators and high voltage substation electronic controls connected to external cables
  - Power generation facility controls were also considered
- Russian scientists under contract to Metatech provided their experience concerning HEMP vulnerability evaluations of their infrastructure
  - External system cable coupling was identified as the main problem for E1 HEMP
- Metatech performed detailed evaluations of geomagnetic storm and E3 HEMP impacts on the U.S. power grid in 2007/2008
  - High likelihood of voltage collapse due to reactive power demand
  - Damage risk to HV and EHV transformers identified
  - Time and cost to replace transformers determined by analysts
  - Hardening techniques and costs identified

A Review of Power Grid Vulnerability from E1 HEMP

- Large geographic footprint of E1 threat environment can result in extensive power grid infrastructure exposure to E1-related failure mechanisms
- Substations: both HV/EHV and distribution class – E1 can cause relay and control device failures
- Control centers: ~150 twenty-four hour manned control centers for regional power grids – E1 can cause control device failures
- Power plants: ~14,500 power plants at ~3000 locations in U.S. – E1 can cause relay and control device failures
- Distribution lines:
  - E1-caused insulator flashover – can create blackouts due to near-simultaneous relay tripping in substations
  - For insulator damage, replacements will be needed to allow for restoration of service to end-users of electricity

HEMP Burst Over Ohio - Line of Sight Circle



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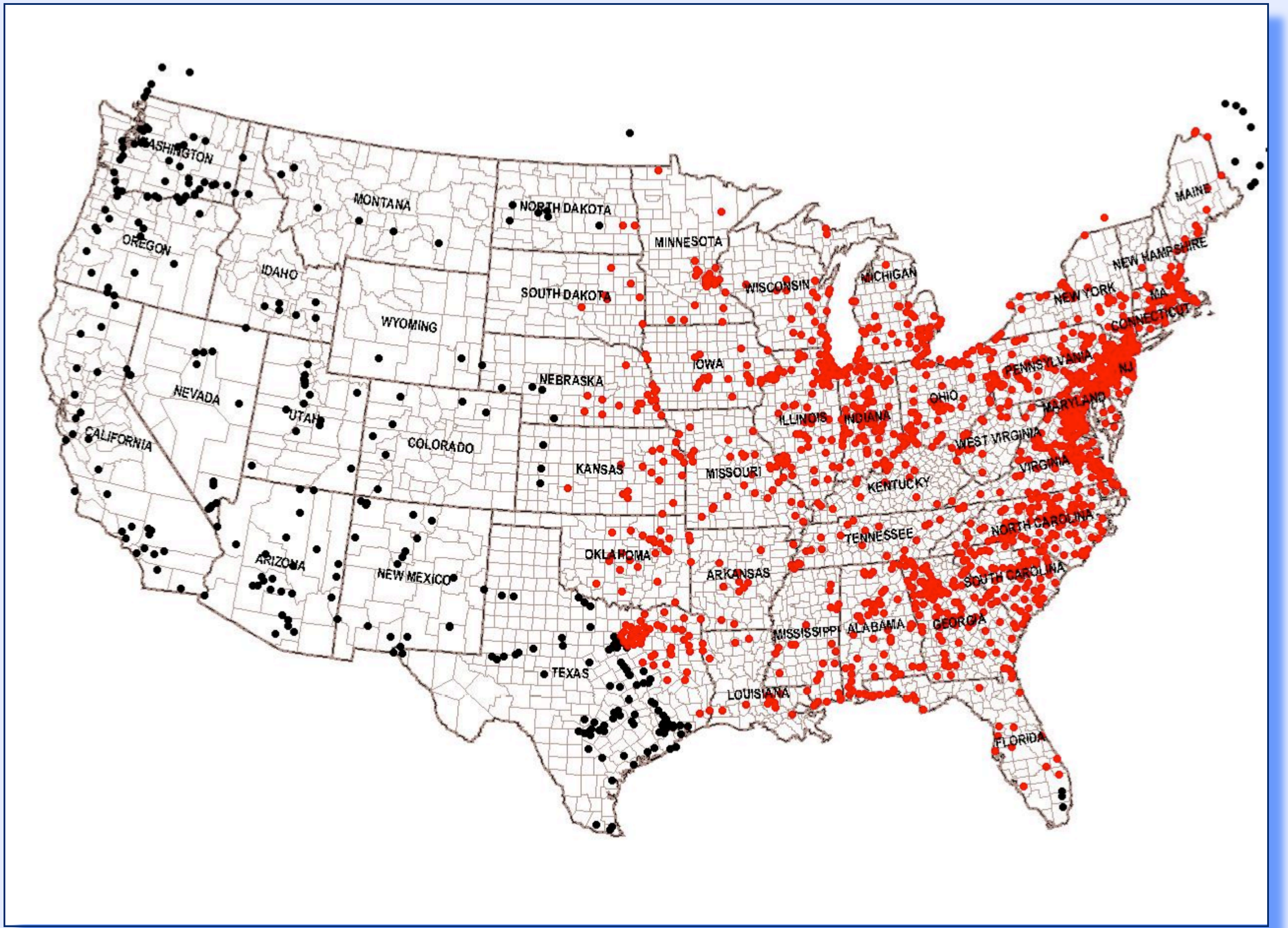
Major HV and EHV Substations Exposed (1765 - 83%)



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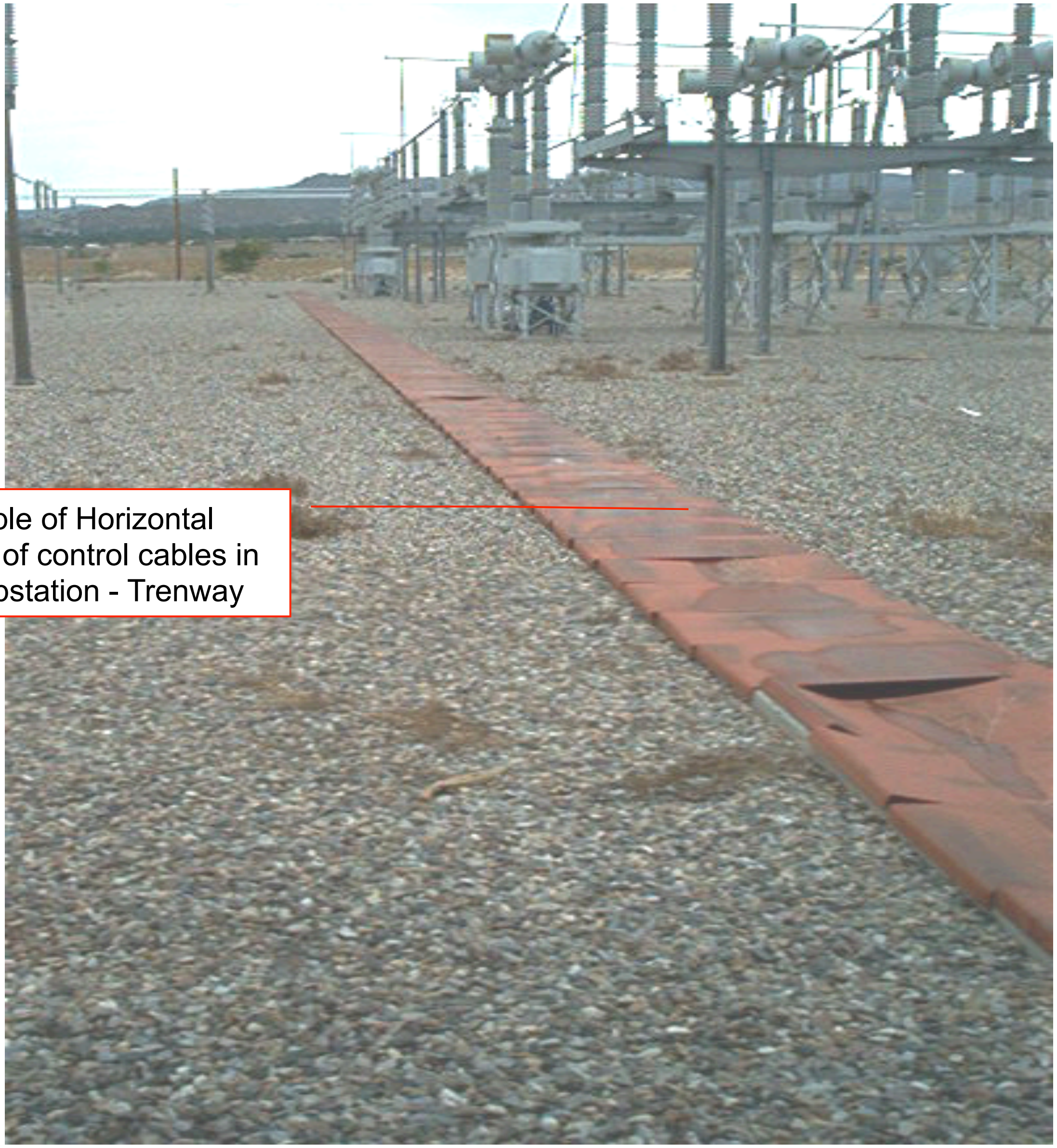
Substation Control Cable Issues



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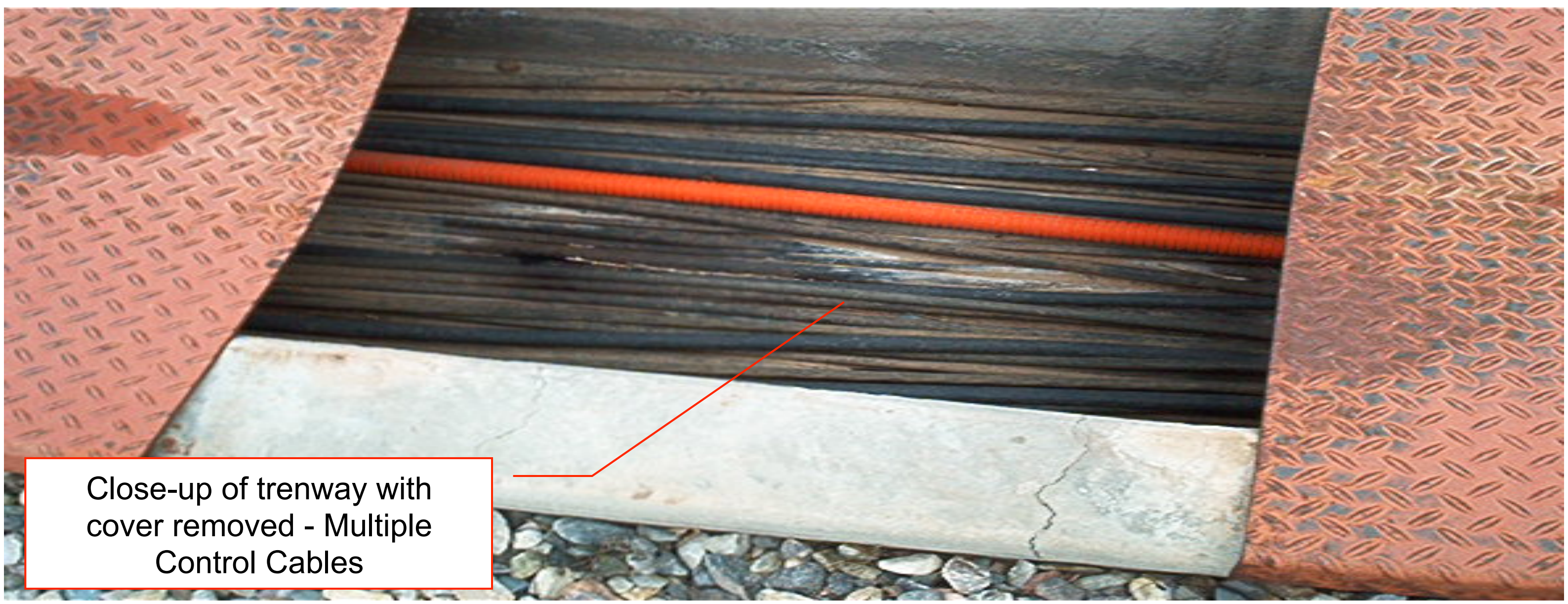
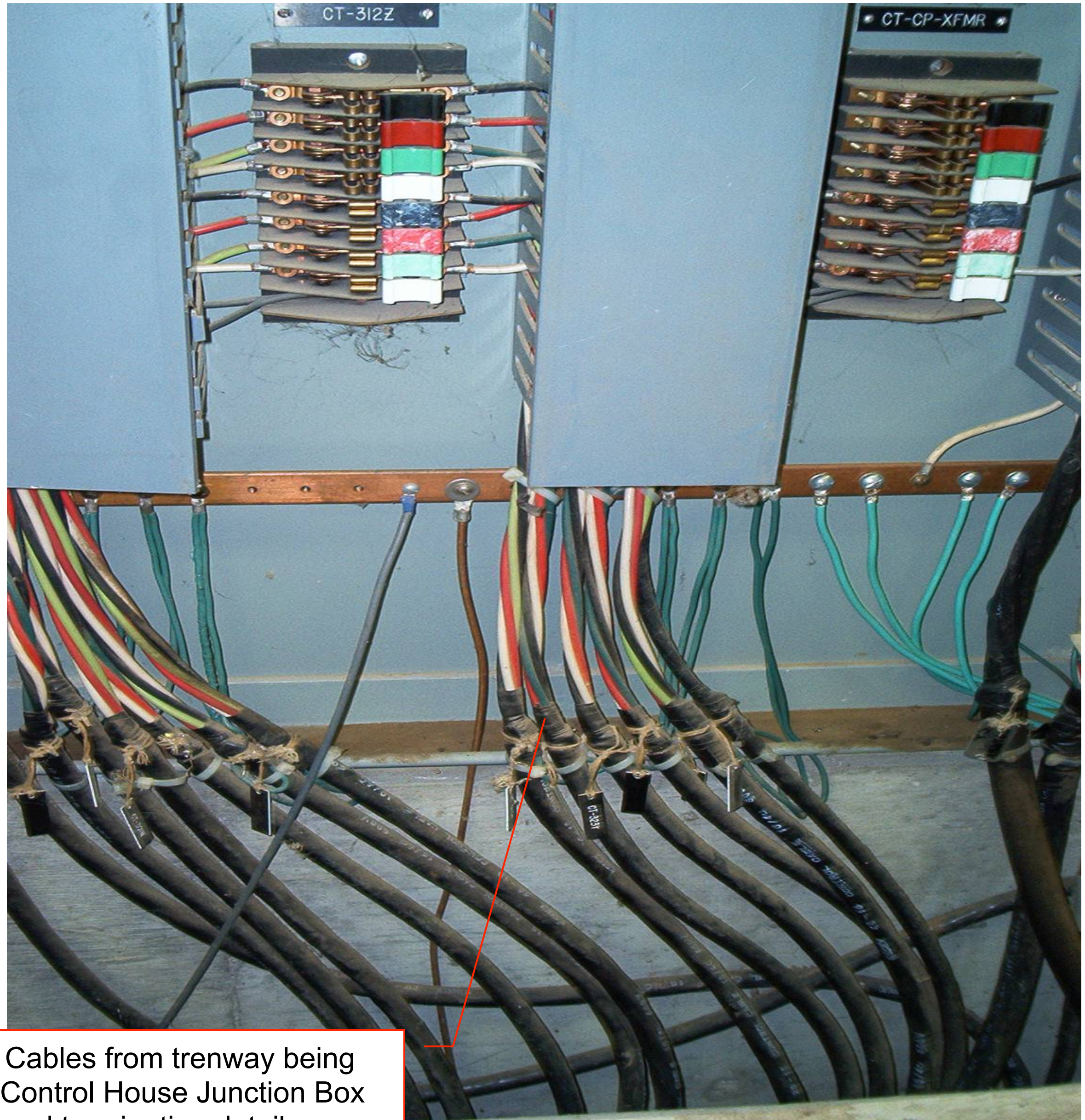
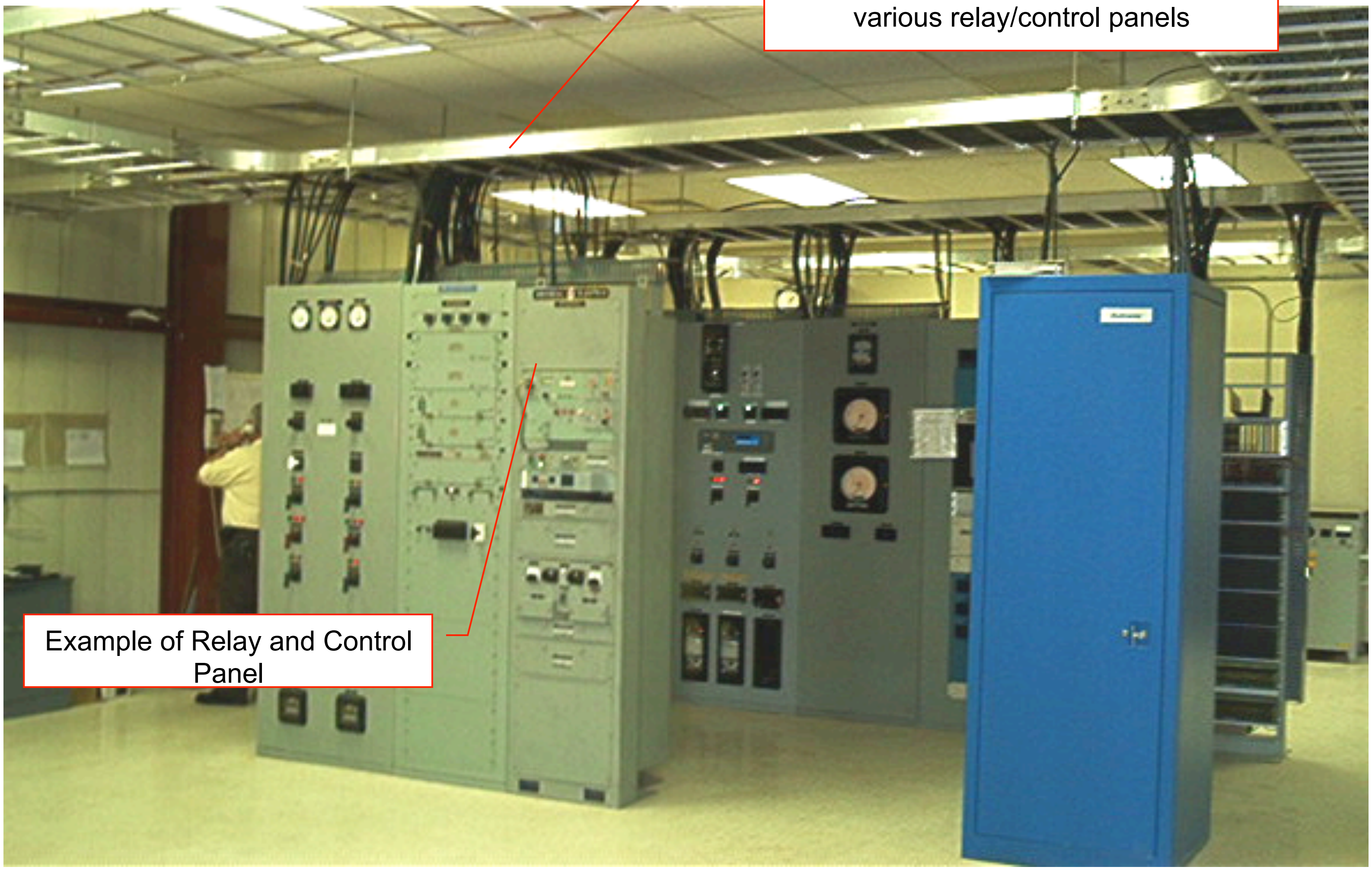
Close-up of trenway with cover removed - Multiple Control Cables


Close-up of trenway with cover removed - Multiple Control Cables



Close-up of Cables from trenway being brought into Control House Junction Box with ground termination details

Control Cables routed via cable tray inside Substation Control house to various relay/control panels



Example of Relay and Control Panel

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Metatech Direct Drive Testing for E1 HEMP

- Priority list of power system control equipment provided by NERC to the EMP Commission -- relays, programmable logic controls, computers, remote terminal units (RTUs), etc.
- Testing was done on every port with checks of all ports after each pulse to determine operability
- Susceptibility testing procedure -- slow increases in peak level
- Damage and upset were separately cataloged
    - Upset and damage begin in the 1-2 kV range
- All results were compared to coupled voltages from different E1 HEMP scenarios and cable orientations
    - Vulnerability estimates were made for the EMP Commission

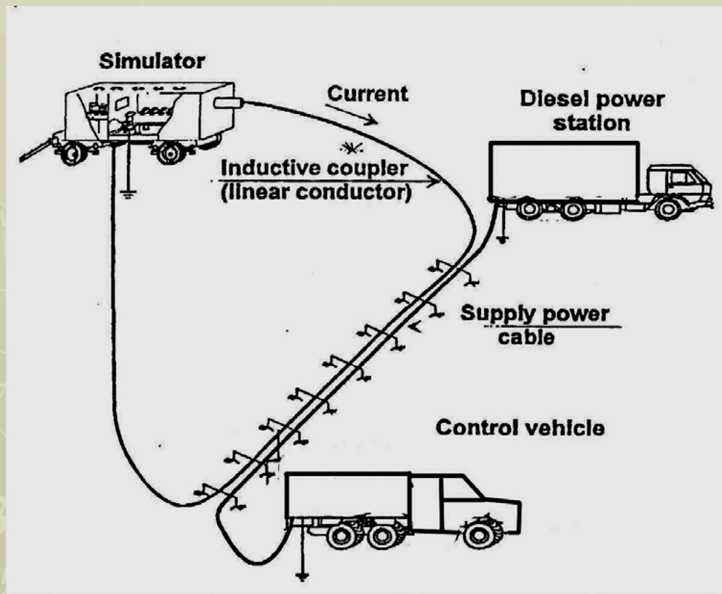
Summary of E1 HEMP Effects on Infrastructure Systems by Russian Scientists

- They reviewed HEMP effects on systems from their nuclear high altitude test experiments and simulators
- Their major conclusion was that systems with cables fail primarily due to the pickup of the HEMP fields on the cables
  - A warning was given that HEMP field simulators are not a good way to properly illuminate and test cables (plane wave issue)
- They indicated that a mobile direct injection simulator was developed in Russia and that power-on testing is crucial to discover failures
- They felt that EMC protection methods are usually effective for protecting against HEMP

Russian E1 HEMP Cable Testing Approach

TESTING POWER SYSTEMS

Failures can occur in powerful systems of power supply

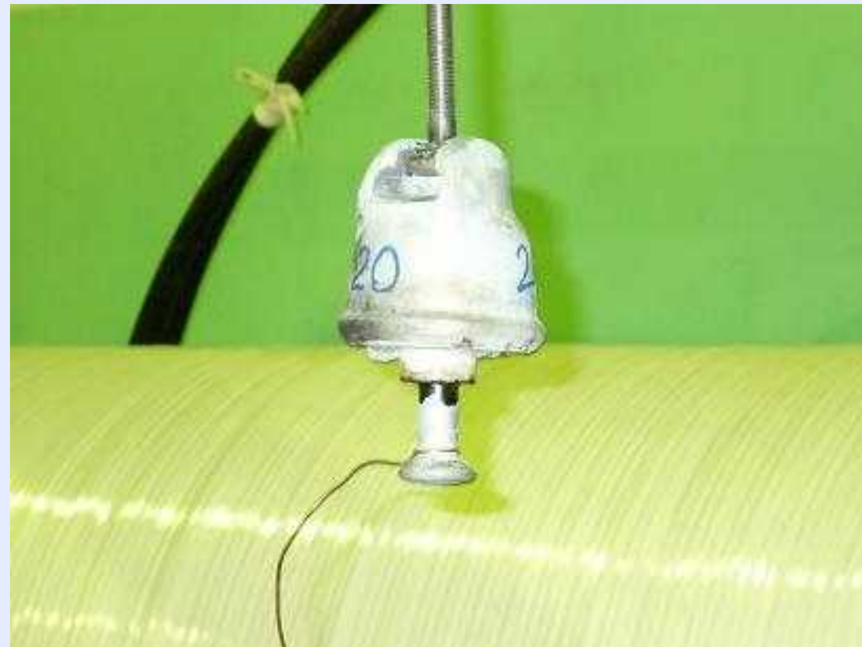


Results of testing the diesel power station

Test specifications	Results
Power off	Serviceability was kept
Power on (0.4 kV)	Irreversible failure of protective device

Insulator Destruction (E1 HEMP)

Before



After

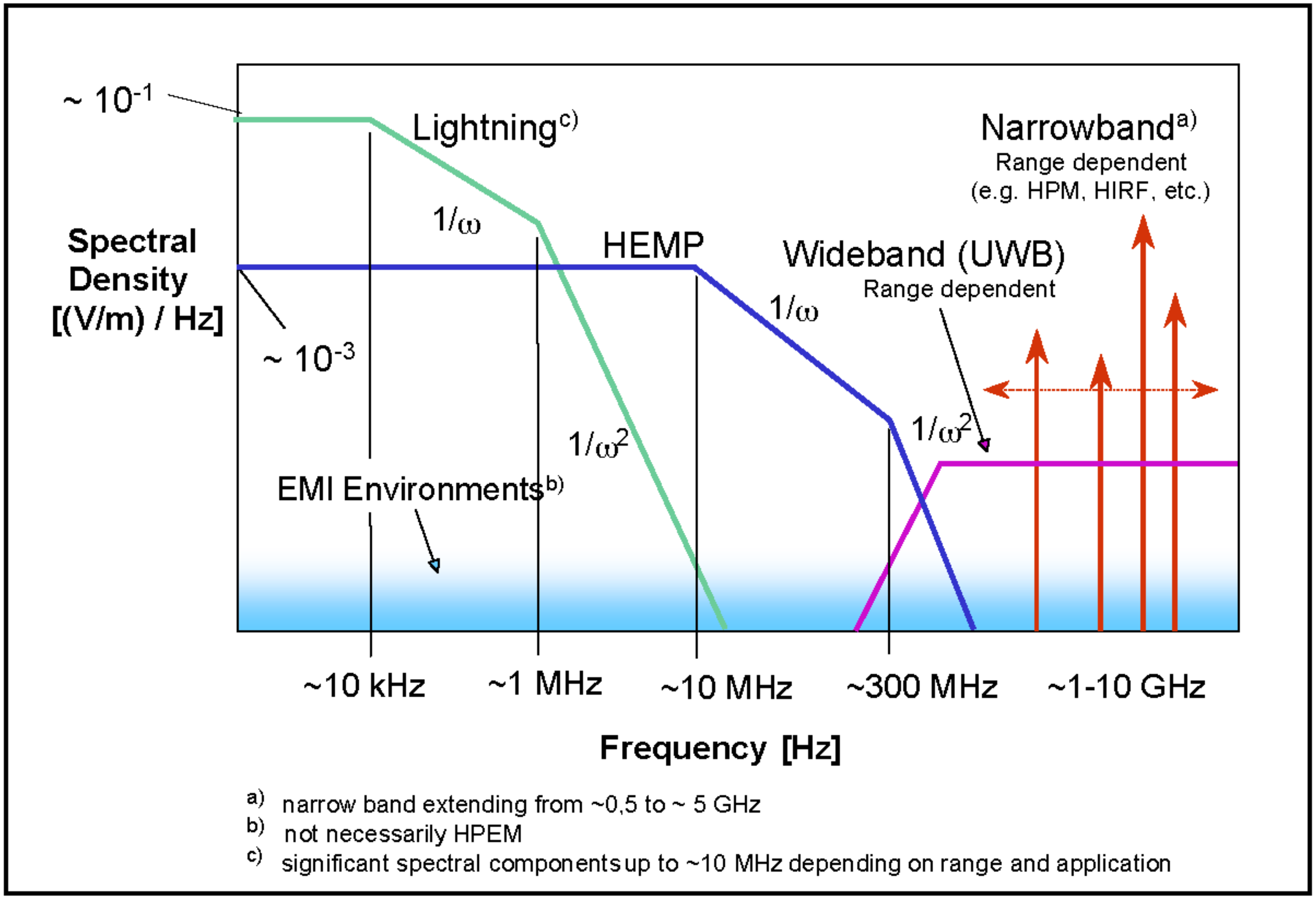
- Damage to a small percentage of the insulators would likely cause a power grid collapse ("instantaneous" loss of load)
  - Need to determine which types and ages of insulators are at risk
  - Need to stockpile spares

HEMP Conclusions - EMP Commission

- One or a few high-altitude nuclear detonations can produce E1 HEMP, simultaneously, over wide geographical areas (arrival within one power cycle from a single burst)
  - E3 HEMP is likely to cause a voltage collapse of the power grid with the possibility of some damage to large transformers
- Unprecedented cascading failure of our electronics-dependent infrastructures could result
  - Power, energy transport, telecom, and financial systems are particularly vulnerable and interdependent
  - HEMP disruption of these sectors could cause large scale infrastructure failures for all aspects of the Nation's life
- Both civilian and military capabilities depend on these infrastructures
- Without adequate protection or planning, full recovery could be prolonged

Overview of Intentional Electromagnetic Interference (IEMI)

Comparison of IEMI Threats with E1 HEMP and Lightning



Ref: IEC Standard 61000-2-13

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What Exactly Is Intentional EMI (IEMI)?

Definition:

Intentional malicious generation of electromagnetic energy introducing noise or signals into electric and electronic systems, thus disrupting, confusing or damaging these systems for terrorist or criminal purposes

(Zurich EMC Symposium, February 1999;
Also IEC 61000-2-13:2005)

Worldwide Scientific Activity in Protecting Commercial Systems Against IEMI

- URSI published a resolution in 1999 dealing with the criminal activities of EM “tools” and the need to protect against the emerging threat
- The International Electrotechnical Commission (IEC) SC77C (EMC: High Power Transient Phenomena) began writing standards to deal with this problem in 1999
- The IEEE EMC Society published a special issue on IEMI in August 2004
- Many EMC conferences are dealing with the subject of IEMI
- Private companies have developed methods of IEMI threat assessments and protection methods

Background for the IEMI Threat

- Electromagnetic (EM) weapons possess an energy source (e.g. battery, capacitors) and an antenna
- They are designed to produce and propagate a high power EM field to a significant distance from the weapon
- These types of weapons have mainly been designed for military purposes
- The basic technology is not difficult to apply for a qualified engineer
- Commercial electronics equipment is not protected against these types of threats
- A new term has been used over the past 18 years to describe this threat and its effects on commercial equipment -- IEMI (Intentional Electromagnetic Interference)

IEEE Spectrum Article – September 2014

- **"Fear of Frying: Electromagnetic weapons threaten our data networks. Here's how to stop them."**
- **Author: Dr. William Radasky**
- **Article describes the threat and protection methods**
  - **Technical details are from peer-reviewed publications**

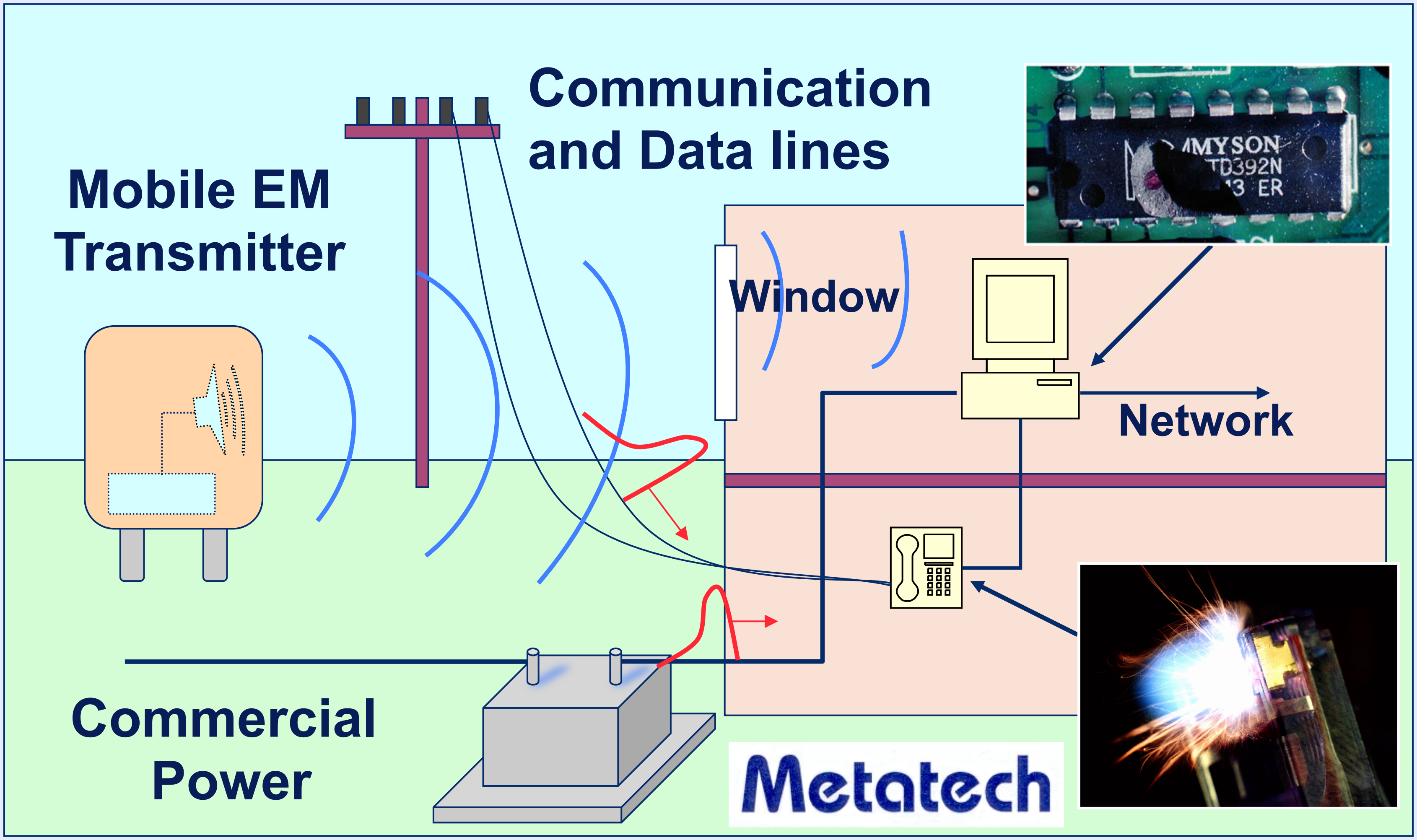
Diehl EM Emitter

- Diehl Munitions Systeme has developed a small interference source (including an antenna)
  - 350 MHz damped sine field
  - 120 kV/m at 1 meter (omni-directional antenna)
  - 30 minute continuous operation (5 pulses per second) or 3 hours in bursts
  - 20 x 16 x 8 inches and 62 pounds
- Demonstration in Summer 2004 at EUROEM
- Improved versions of this source have been developed since then (4 times larger fields)

JOLT IRA Hyperband Generator

- AFRL has developed an extremely powerful IRA system that produces hyperband pulses
  - E*r = 5.3 MV
  - pulse width ~1 ns

Coupling Paths for Radiated IEMI Fields



Impacts of IEMI on the Power System

- The IEMI electromagnetic fields are in a similar frequency band as the E1 HEMP discussed earlier
- The impacts on the power grid will be similar to that from E1 HEMP
  - Substation control electronics can be affected by nearby EM weapons
  - Control center computer operations could be affected
  - Power generation controls and inverters are also at risk (including distributed generators – solar, wind)
- Major difference is that the IEMI is a local threat and therefore does not approach the same exposure area level as E1 HEMP, unless a coordinated attack is performed
- Protection methods for electronics will be similar for IEMI and E1 HEMP
  - In addition security measures such as physical separation of attack locations and detectors can be used for IEMI

Very Recent IEMI Developments

- Several US power companies are combining E1 HEMP and IEMI hardening measures for control centers
- The European Union funded over 15 Million Euros worth of IEMI critical infrastructure research projects which finished in 2015
- New IEMI detectors are being designed for use in critical infrastructures
- New papers indicate that IEMI is a threat for radiation detectors
- New papers indicate that IEMI is a serious threat to video cameras
- New papers indicate that 3-layer energy efficient glass may provide up to 60 dB of 1-10 GHz protection

Overview of Geomagnetic Storm Impacts on the Power Grid

Introduction - 1

- Over the past 28 years the effects of geomagnetic storms have been noted on high-voltage power grids throughout the world
  - March 13, 1989 power blackout in Quebec
  - Measurements of large transformer neutral currents in the U.S., Japan, UK, Norway and Sweden during "small" storms
- Detailed models of power grids have been developed with excellent results as compared to past storms
- It is possible to analyze complex power grids and determine the regions of highest vulnerability
  - Analysis (and experience) indicates that the higher the voltage of operation of a local grid, the more vulnerable it is to geomagnetic storms

Introduction - 2

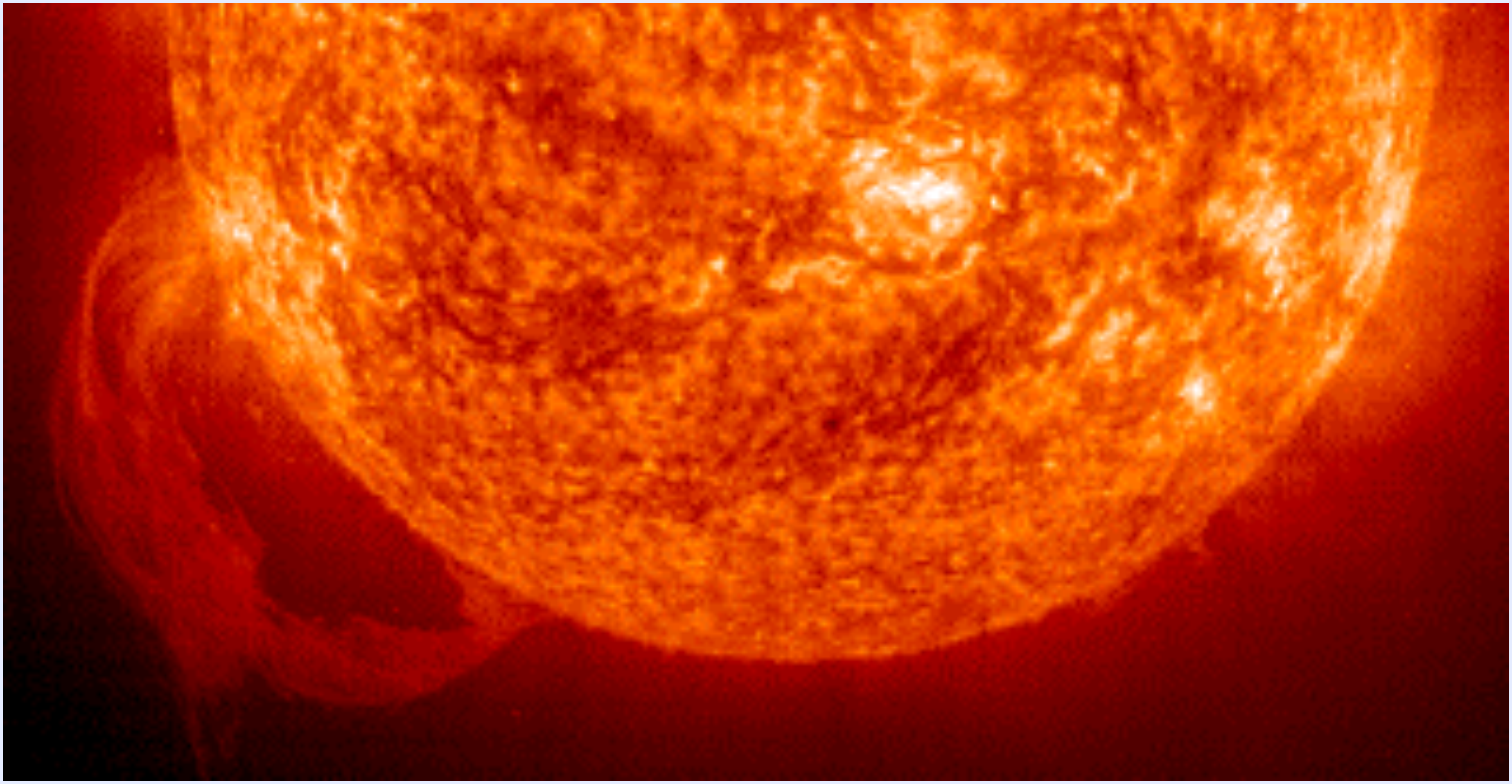
- It is noted that geomagnetic storms are created by solar activity, and large storms can create low-frequency electric fields on the order of a few V/km or higher
- A high-altitude nuclear burst creates a similar waveform (E3 HEMP) on the Earth's surface with electric fields as high as 40 V/km (IEC 61000-2-9)
  - EMP Commission will be providing new waveform in 2017
- Because geomagnetic induced currents (GICs) can be modeled and measured, validation of the models can be performed
- E3 HEMP fields and induced power system currents can be calculated with the same models

A Review of Power Grid Vulnerability to GIC Events

- Geomagnetic storms are disturbances in the Earth's normally quiescent geomagnetic field caused by intense solar activity
- A rapidly changing geomagnetic field over large regions will induce Geomagnetically-Induced Currents (i.e. GIC, a quasi-DC current) to flow in the interconnected HV/EHV/UHV bulk transmission system
- GIC flow in transformers will cause half-cycle saturation which can significantly increase reactive power demand and production of even and odd harmonic currents and waveform distortion
- Because large regions of the power grid can be impacted simultaneously, these disturbances can cause multiple correlated failures and voltage regulation problems which exceed "N-1" NERC criteria
- Metatech has performed threat assessments of electric power grids in England, Norway, Sweden, the U.S. and portions of Japan

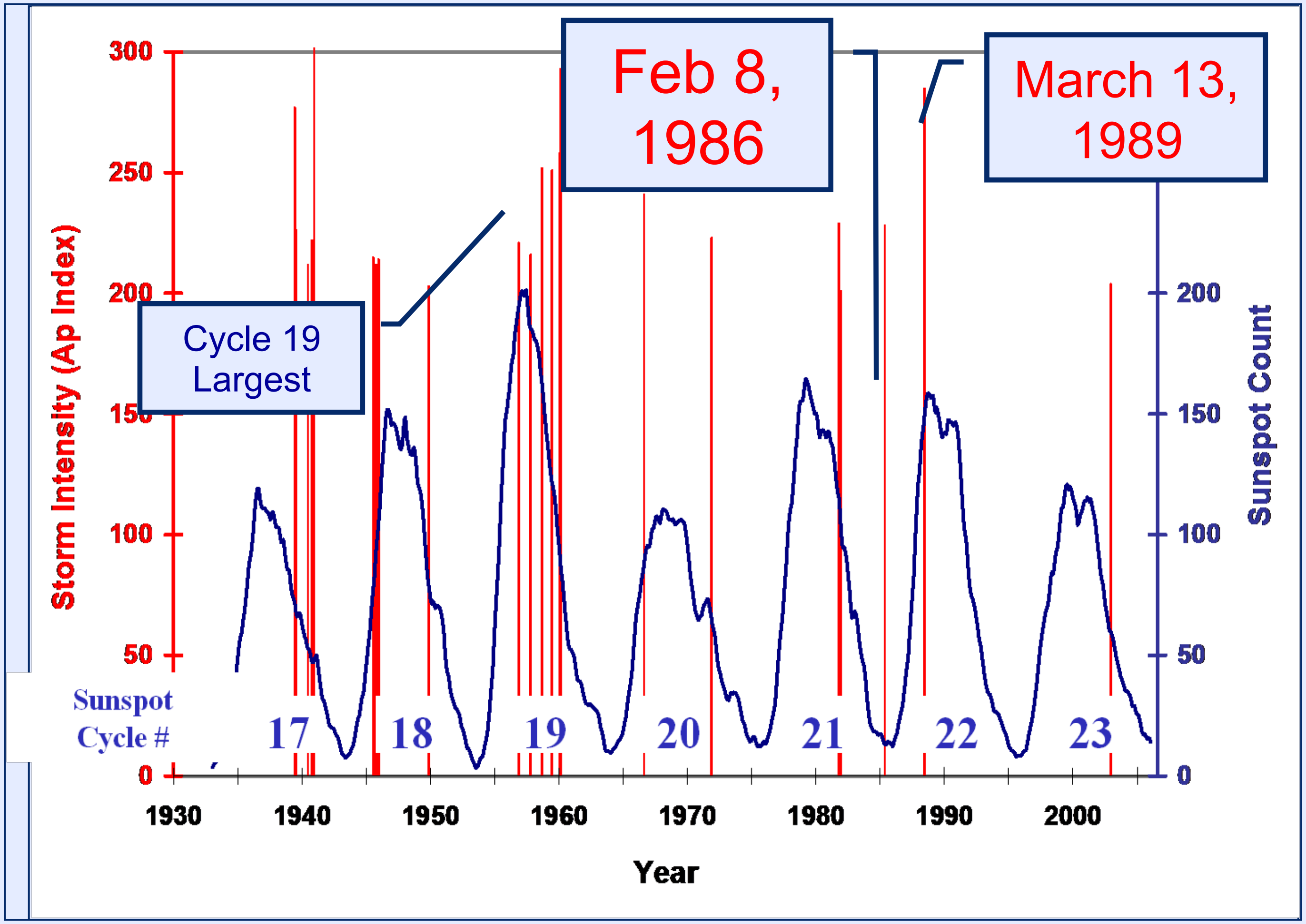
A Brief Overview of Sunspot and Associated Solar Activity and Resulting Geomagnetic Storms

Note: This is a coronal mass ejection (not a flare)!



SOHO Image June 9, 2002

Sunspot Cycle and Large Geomagnetic Storm Events



Large Geomagnetic Storms can and do occur at anytime in the Sunspot Cycle and not just around the Peaks

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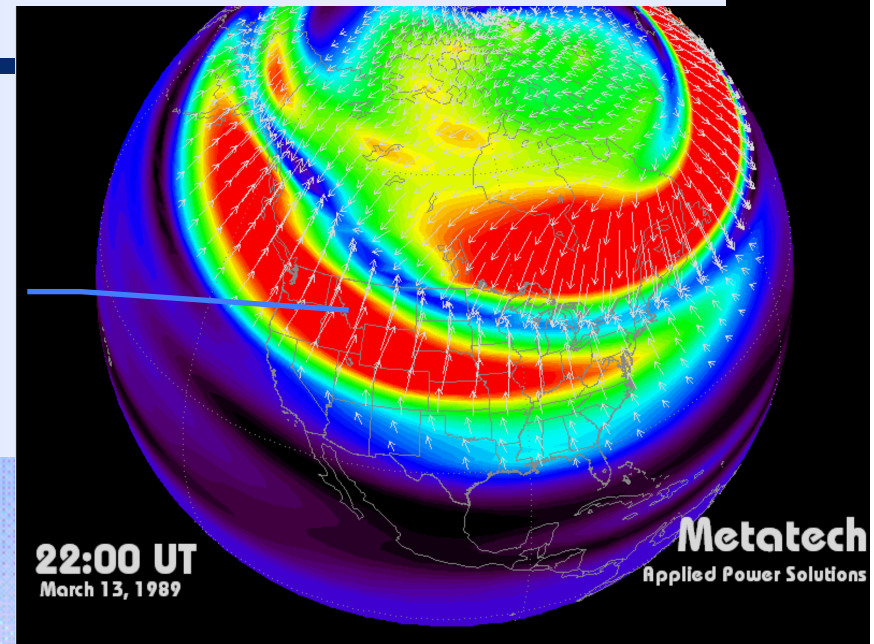
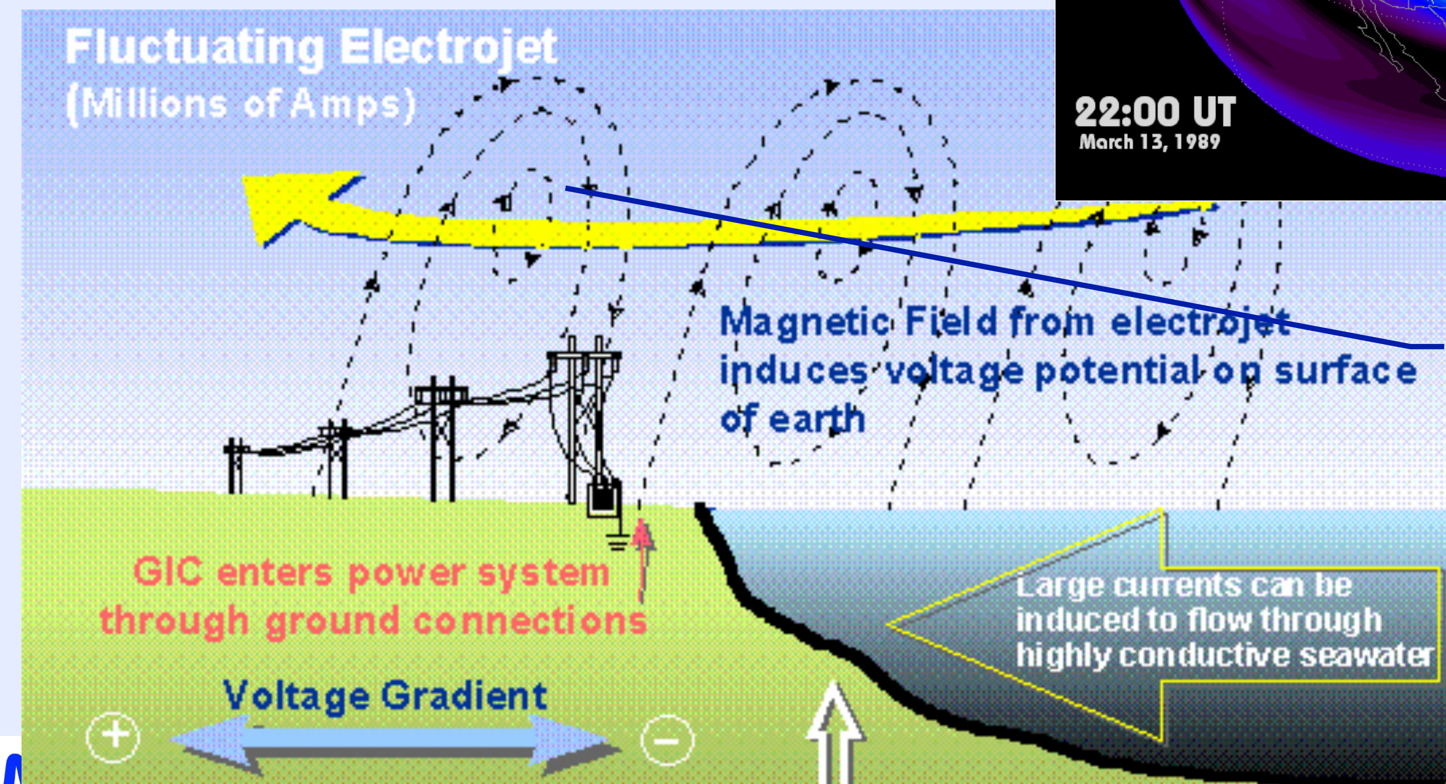
Geomagnetic Storms and Large Power Grids

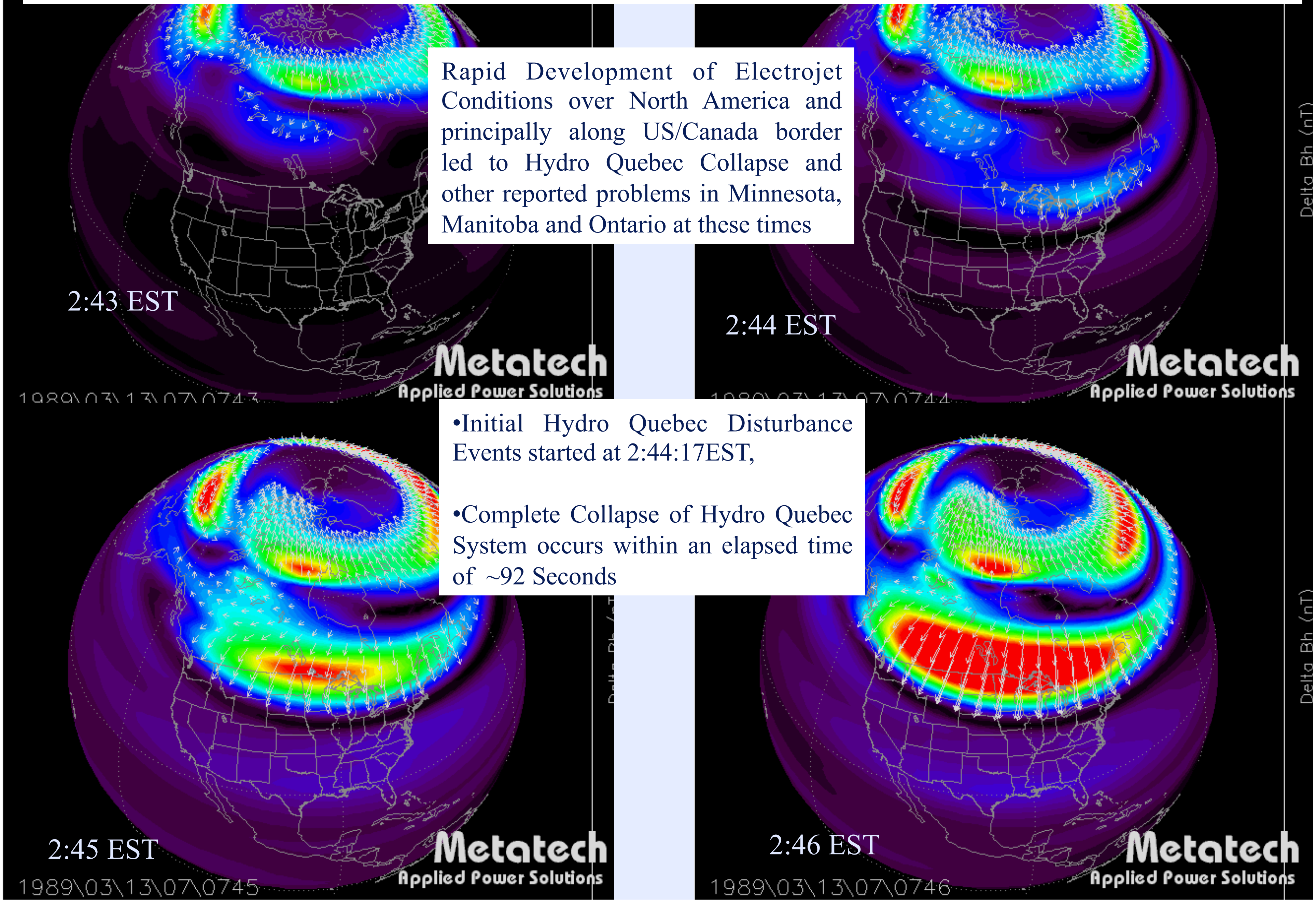
Storms have Continent-Wide Footprints





Field Disturbances from Electrojet Current Couple to Power Systems

March 13, 1989 – 4 Minutes of a Superstorm



Rapid Development of Electrojet Conditions over North America and principally along US/Canada border led to Hydro Quebec Collapse and other reported problems in Minnesota, Manitoba and Ontario at these times

- Initial Hydro Quebec Disturbance Events started at 2:44:17EST,
- Complete Collapse of Hydro Quebec System occurs within an elapsed time of ~92 Seconds

Geomagnetic Storms Can Cause Permanent Transformer Damage due to Overcurrent and Stray Flux Heating

These Key Assets may take a *Year or More to Replace*

Salem Nuclear Plant
GSU Transformer
Failure, March ‘89

Damage due to one storm

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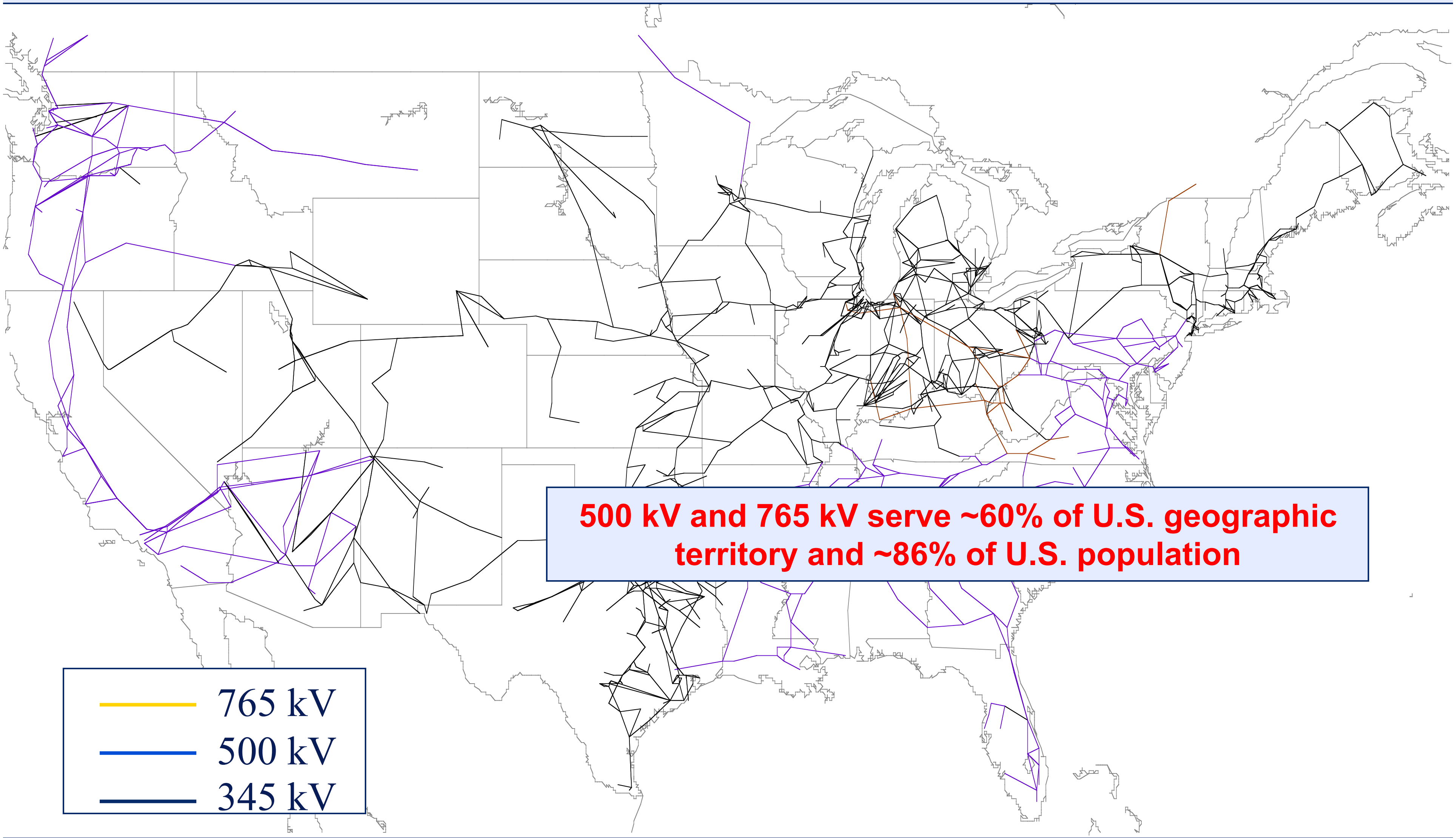
U.S. High-Voltage Transmission Network Model for GIC Simulation



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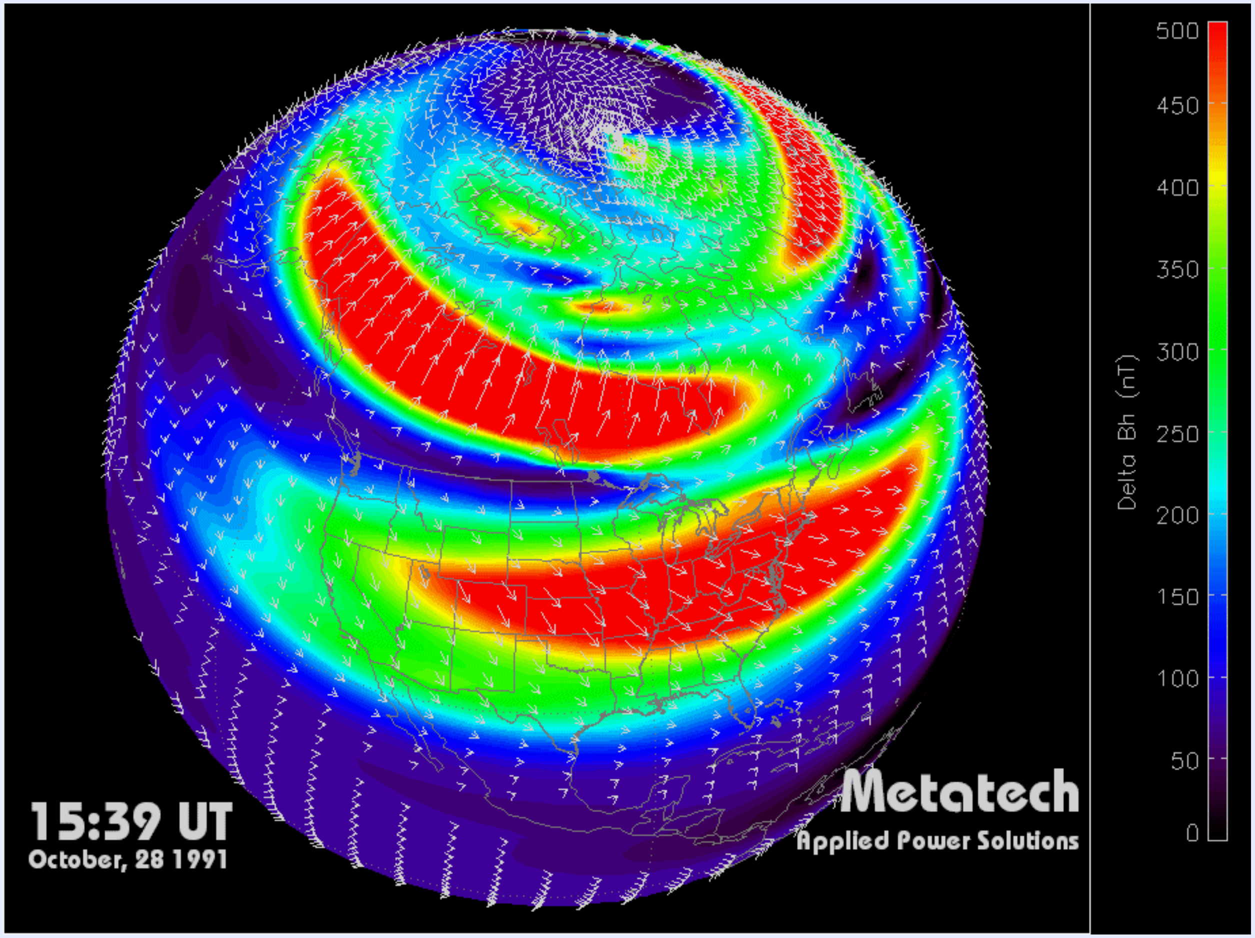
Note: Only the EHV power network is modeled in this case

Geomagnetic Disturbance Conditions
15:39 UT on Oct 28, 1991



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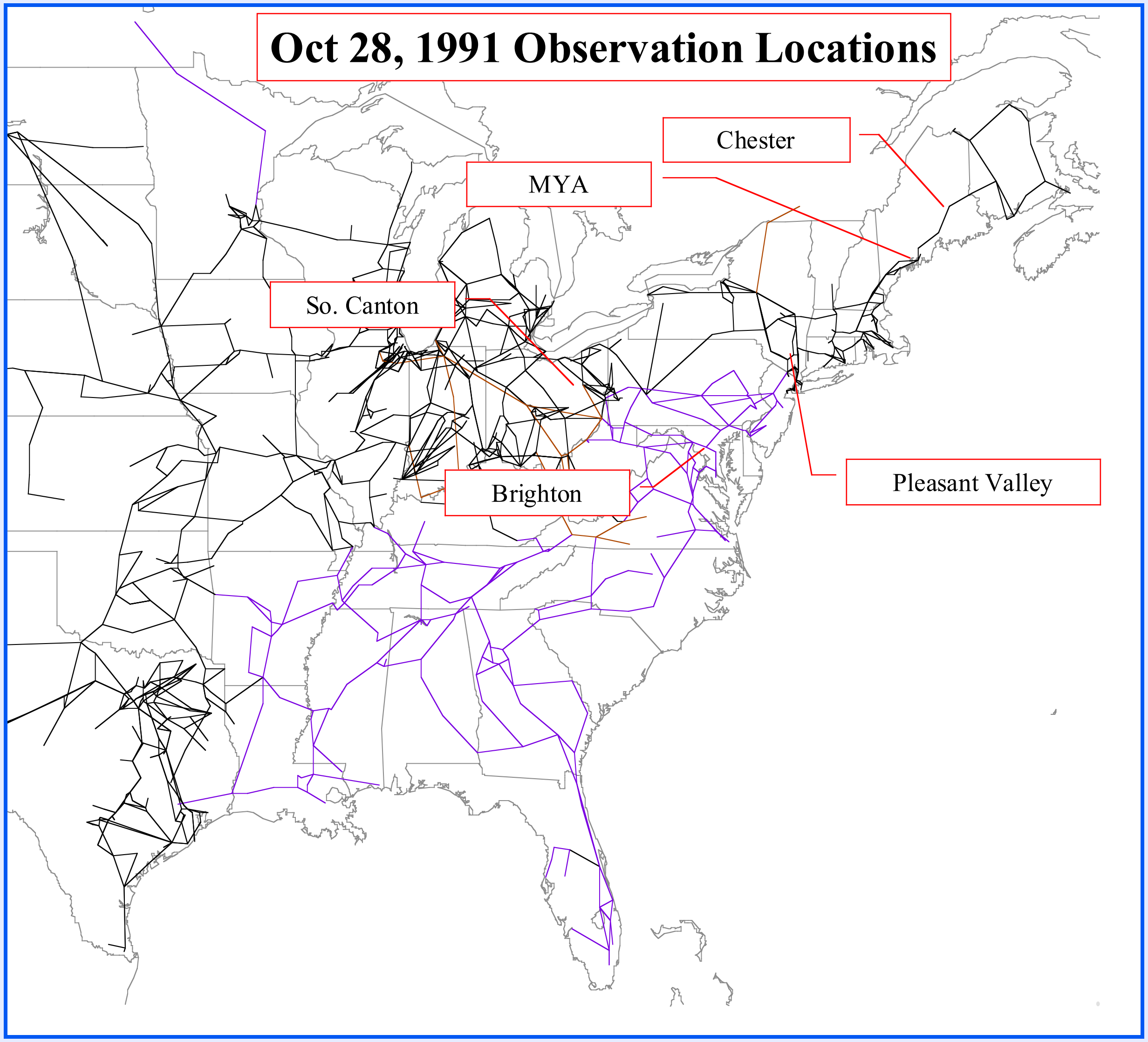
Locations of GIC Measurements on Oct 28, 1991



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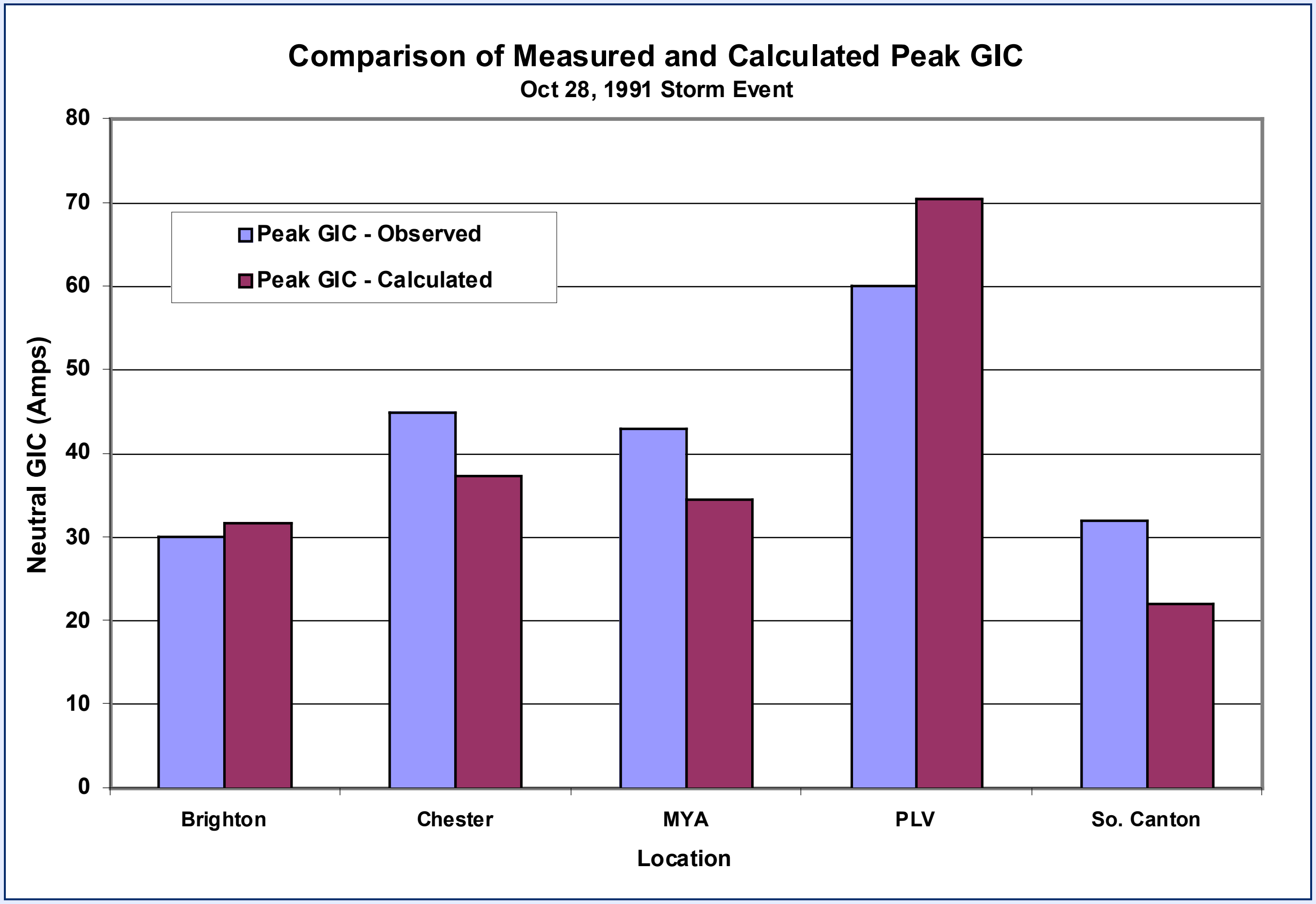
Code/Data Peak GIC Comparisons



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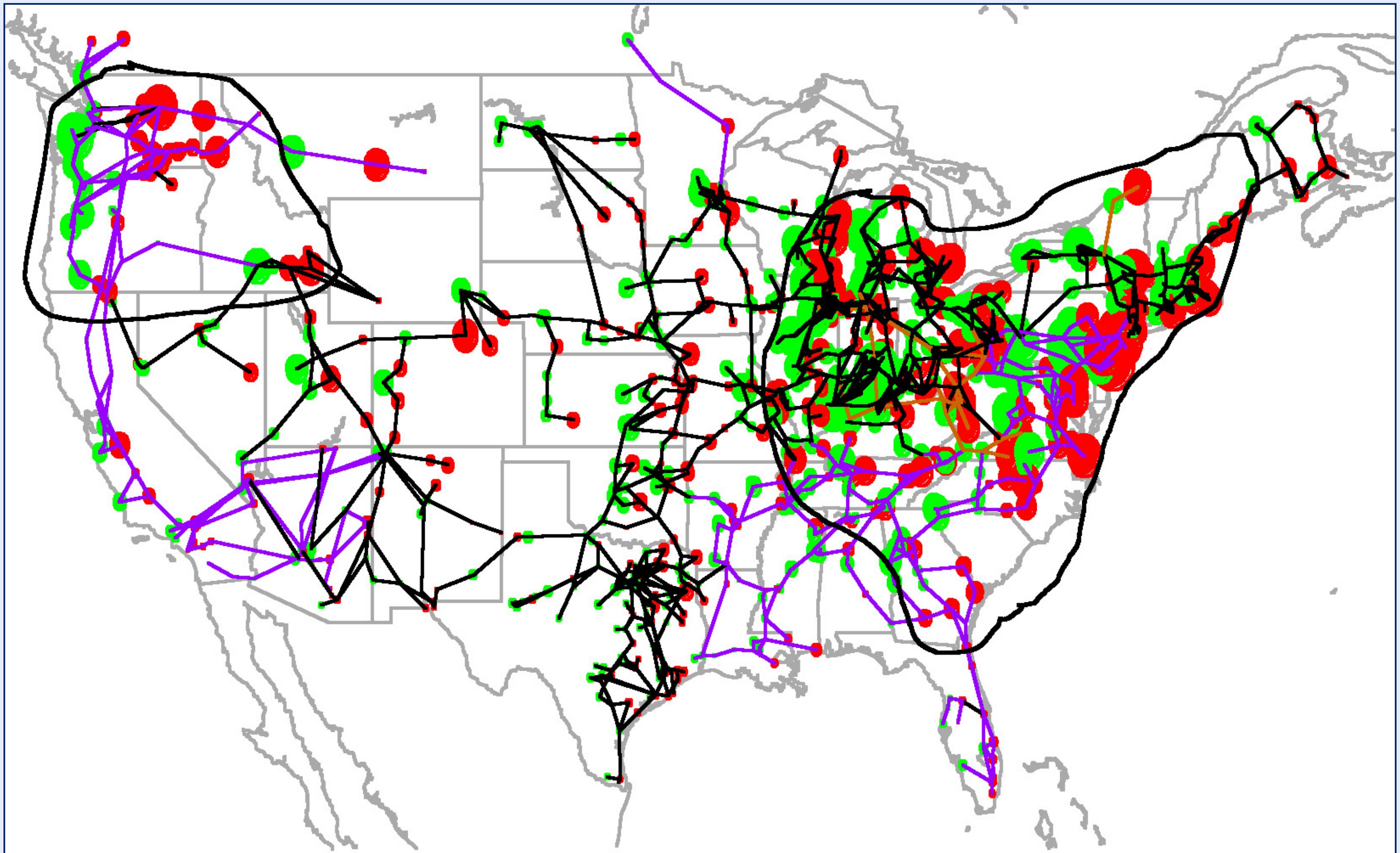
Impact (Blackouts) of a Large (4800 nT/min) Geomagnetic Storm over the U.S.



100 Year Geomagnetic Storm – 50 Degree Geomagnetic Disturbance Scenario

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Protection!

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EM Protection -- Not New!

- Protection from electromagnetic fields is not a new discipline
- Electromagnetic compatibility (EMC) engineers have been assessing new threats and developing protection and test methods for > 50 years
  - Radar can affect aircraft and nearby commercial facilities
  - Radio station impacts on new construction nearby
  - Hospital electronics need protection from MRI machines
  - Protection against cellular phones (major initiative that continues today -- gas stove example and new efforts to deal with cellular phones inside of modern motor vehicles)
- These EM threats are recognized and dealt with as they occur
- Not as easy for low probability events to evaluate and fix the problem (when recognized, it may be too late)
- Begin the process with an assessment of the impact of HEMP and IEMI

IEMI and E1 HEMP Assessments

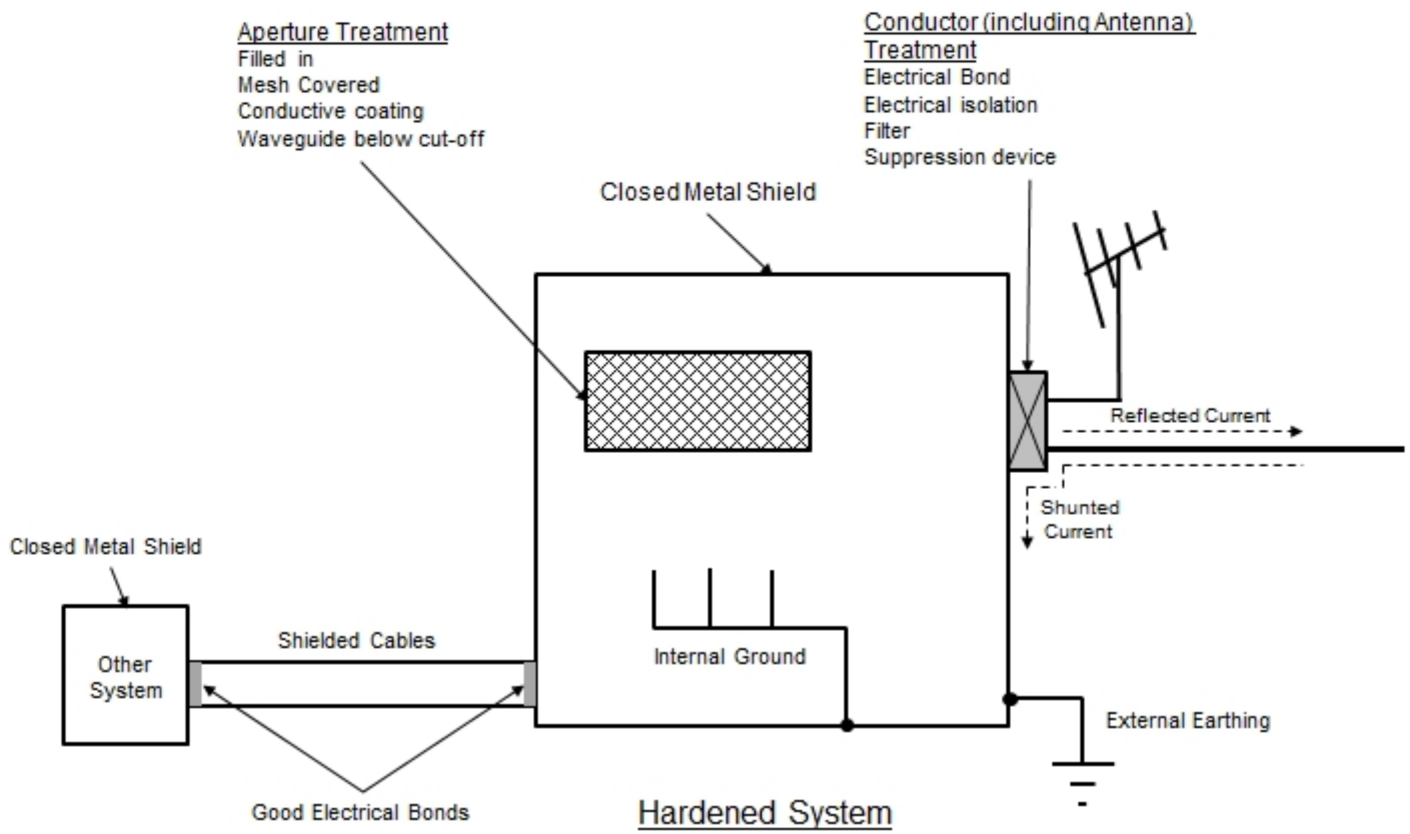
Assessment Steps

- Building shielding effectiveness
  - Measure building EM attenuation
- External EM
  - Select HEMP parameters
  - IEMI: Select IEMI weapon parameters, determine closest stand-off distance, and calculate EM levels at the building
- Internal EM field levels
  - Apply building attenuation to external EM levels
- Cable coupled voltages
  - Identify cable lengths
  - Apply statistical coupling approach, using EM levels and cable lengths
  - Evaluate contribution of external cables entering building
- Equipment vulnerability voltages
  - Determine dominant internal equipment and estimate typical upset and damage voltage levels
- Protection deficit
  - Protection needed: compare induced voltages and vulnerability levels
- Protection measures
  - Review options for lowering coupled voltage or strengthening equipment

Shielding Effectiveness Measurements of Typical Buildings

Shielding Measurements		
Nominal Shielding, dB	Room	Shielding, dB
0	All wooden bldg	2
5	Room under wood roof	4
	Wood bldg-room 1	4
	Concrete – no rebar	5
	Wood bldg-room 2	6
10	Conc.+rebar-room 1	7
	Conc.+rebar-room 2	11
	Conc.+rebar-room 3	11
20	Conc.+rebar-room 4	18
30	Metal bldg	26
	Conc.+rebar-well prot. room	29

Examples of EM Protection Application



Ref: IEC 61000-5-10

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General Protection Options

- Use high quality external grounding for external cables
- Improve the building/room shielding effectiveness
  - External metal sheeting
  - Internal metallic walls
  - Shield rooms or racks
  - New metallic building
- Improve shielding/grounding of internal cabling
- Apply cable ferrites on metallic cables
- Add filters and/or surge arresters at metallic cable connections (including antenna connections)
- Replace metallic with fiber optic cables (w/o metal)
- Improve security measures for IEMI (distance, monitoring, etc.)

IEC HPEM Standardization Program

- The International Electrotechnical Commission (IEC) develops electrical standards for the world -- founded in 1906 (www.iec.ch)
- The IEC has been developing HEMP and IEMI standards and reports since 1989 (28 years)
  - IEC SC 77C was formed in 1992
- Initial emphasis was to provide the means to protect civil electronics equipment from the effects of HEMP generated by high-altitude nuclear bursts
- Scope of work in SC 77C expanded in June 1999 to include man-made EM transient threats with emphasis on IEMI
- The IEEE, ITU-T and Cigré are also developing publications to aid in the protection of the critical infrastructures from these threats

IEC HEMP and IEMI Publications – 2017 (22)

Series					
61000-1- (General)	-3 HEMP Effects On Systems	-5 HPEM Effects On Systems			
61000-2- (EM Environment)	-9 HEMP Radiated Environment	-10 HEMP Conducted Environment	-11 Classification Of HEMP Environments	-13 HPEM Environments	
61000-4- (Testing and Measuring Techniques)	-23 Test Methods Radiated	-24 Test Methods Conducted	-25 HEMP Immunity Tests	-32 HEMP Simulator Compendium	-33 HPEM Measurement Methods
	-35 HPEM Simulator Compendium	-36 IEMI Immunity Test Methods			
61000-5- (Installation and Mitigation Guidelines)	-3 HEMP Protection Concepts	-4 Specifications For Radiated Protection	-5 Specifications For Conducted Protection	-6 Mitigation Of External EM Influences	
	-7 EM Code	-8 HEMP Protection Methods For The Distributed Civil Infrastructure	-9 System-level Susceptibility Assessments For HEMP and HPEM	-10 Application Guide	
61000-6- (Generic Standards)	-6 Generic Standard For HEMP Immunity				

IEC Publication Relevant to HEMP and IEMI Protection

- **IEC TS 61000-5-10 Ed. 1.0 (2017-05): Electromagnetic compatibility (EMC) – Part 5-10: Installation and mitigation guidelines – Guidance on the protection of facilities against HEMP and IEMI**
  - This part of IEC 61000 provides guidelines to protect commercial facilities from the high power electromagnetic disturbances of high-altitude electromagnetic pulse (HEMP) and intentional electromagnetic interference (IEMI). These guidelines are developed from the entire body of IEC SC 77C publications
  - This document is applicable to both existing facilities and new buildings when the customer has decided that protection of critical electronics from HEMP and IEMI is important to the function of the facility

New IEC EMC Standard for Power Systems

- IEC 61000-6-5 Ed. 1.0 (2015-10): Electromagnetic Compatibility (EMC) – Part 6-5: Generic Standards – Immunity for equipment used in power station and substation environments
  - This international standard sets immunity test requirements for equipment intended for use in the generation, transmission and distribution of electricity and related telecommunication systems
  - The electromagnetic environments encompassed by this standard are those which exist at locations in power stations, and in high and medium voltage substations

- This standard requires all IEC product committees apply these immunity tests in their EMC standards. IEC 61850-3 will need to update their requirements due to added tests, higher levels and improved test performance criteria

- From a HEMP and IEMI protection point of view EMC equipment immunity is important to develop a strategy for protection

Dr. William Radasky Biography

Dr. Radasky received his Ph.D. in Electrical Engineering from the University of California at Santa Barbara in 1981. He has worked on high power electromagnetics (HPEM) applications for more than 48 years. He has published over 500 reports, papers and articles dealing with transient electromagnetic environments, effects and protection during his career. In recent years he has worked extensively in performing assessments for critical infrastructures to the threats of HEMP, IEMI and severe geomagnetic storms. He is Past Chairman of IEC SC 77C (EMC: High Power Transient Phenomena), Chairman of IEEE EMC Society TC-5 (High Power EM), and a Working Group Convener for Cigré C4. He founded Metatech Corporation in 1984 in California and is the President and Managing Engineer. Dr. Radasky is very active in the field of electromagnetic compatibility (EMC) standardization, and he received the Lord Kelvin Award from the IEC in 2004 for outstanding contributions to international standardization. He is an IEEE Life Fellow and a registered Professional Engineer in electric engineering.

Thank you for your attention!
Questions?