HEMP, IEMI and Severe Geomagnetic Storm Effects on Critical Infrastructures

Presentation to
IEEE EMC Santa Clara Valley Chapter

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Outline of Talk

- Terminology -- What are we talking about?
- Overview of high-altitude electromagnetic pulse (HEMP)
- Overview of Intentional Electromagnetic Interference (IEMI)
- Severe geomagnetic storms
- Protection issues and standards
- What's New?

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 the United States 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

- While one could argue about the merits of various definitions, it is still confusing. Standardized definitions (IEC and IEEE) are used in this presentation

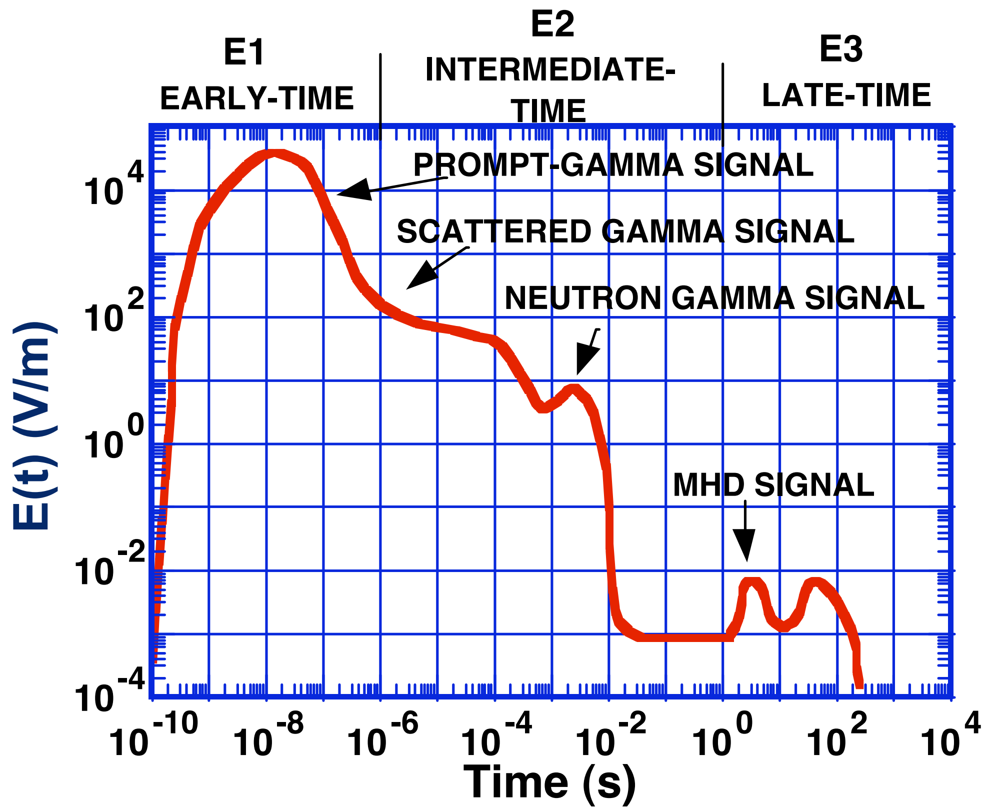
- In this presentation we will discuss three electromagnetic threats to the commercial power system
  - HEMP (high altitude electromagnetic pulse) from a nuclear detonation in space
  - Intentional electromagnetic interference (IEMI) which is caused by the use of electromagnetic weapons by criminals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

My Capabilities and Experience

- This author has been involved in the protection of military and commercial systems from electromagnetic threats since 1968
  - Active in the development of military standards to define the HEMP environment and to test cables entering military facilities
  - Founded a corporation in 1984 to evaluate and protect against electromagnetic (EM) threats
  - Co-developed a capability to assess and protect power systems against geomagnetic storms and HEMP
  - Consultant to the Congressional EMP Commission
  - Published over 400 reports, conference papers and articles dealing with EM transients and protection

- Chair of several International standardization efforts for EM threats
  - IEC SC 77C, "EMC: High power transients" since 1992
  - IEEE EMC Society Committee TC-5 on High Power EM
  - Cigré Working Group to protect power substations against IEMI

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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Impacts of EM Threats on Power System

- E1 HEMP (initial part)
  - Damage to power distribution insulators on lines
  - Damage to electronic equipment inside substation buildings, control centers and power plants
  - Damage to building power transformers and telephone panels in control centers
- E3 HEMP (last part) and Geomagnetic Storms
  - Voltage collapse of the public power grid and damage to EHV transformers (> 345 kV)
  - Some impacts due to power harmonics injected into buildings, affecting UPS and backup power systems
- IEMI
  - Upset and damage to control and communications equipment in substations
  - Upset and damage to computers in control centers and power plants

Impacts of EM Threats on Other Critical Infrastructures

- E1 HEMP (initial part)
  - Damage to electronic equipment inside telecom central offices
  - Damage to electronic equipment inside financial institutions
- E3 HEMP (last part) and Geomagnetic Storms
  - Voltage collapse of the public power grid and damage to EHV transformers (> 345 kV) creating long term power outages
  - Some impacts due to power harmonics injected into buildings, affecting UPS and backup power systems
- IEMI
  - Upset and damage to control and communications equipment inside telecom central offices
  - Upset and damage to computers in control centers for any infrastructure

Overview of HEMP

HEMP Threat: Historical Evidence (US)

- STARFISH event, July 9, 1962
  - Rocket launch from Johnston Is.
  - 1.4 MT, 400 km HOB
  - 1400 km from Honolulu
- HEMP effects felt 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

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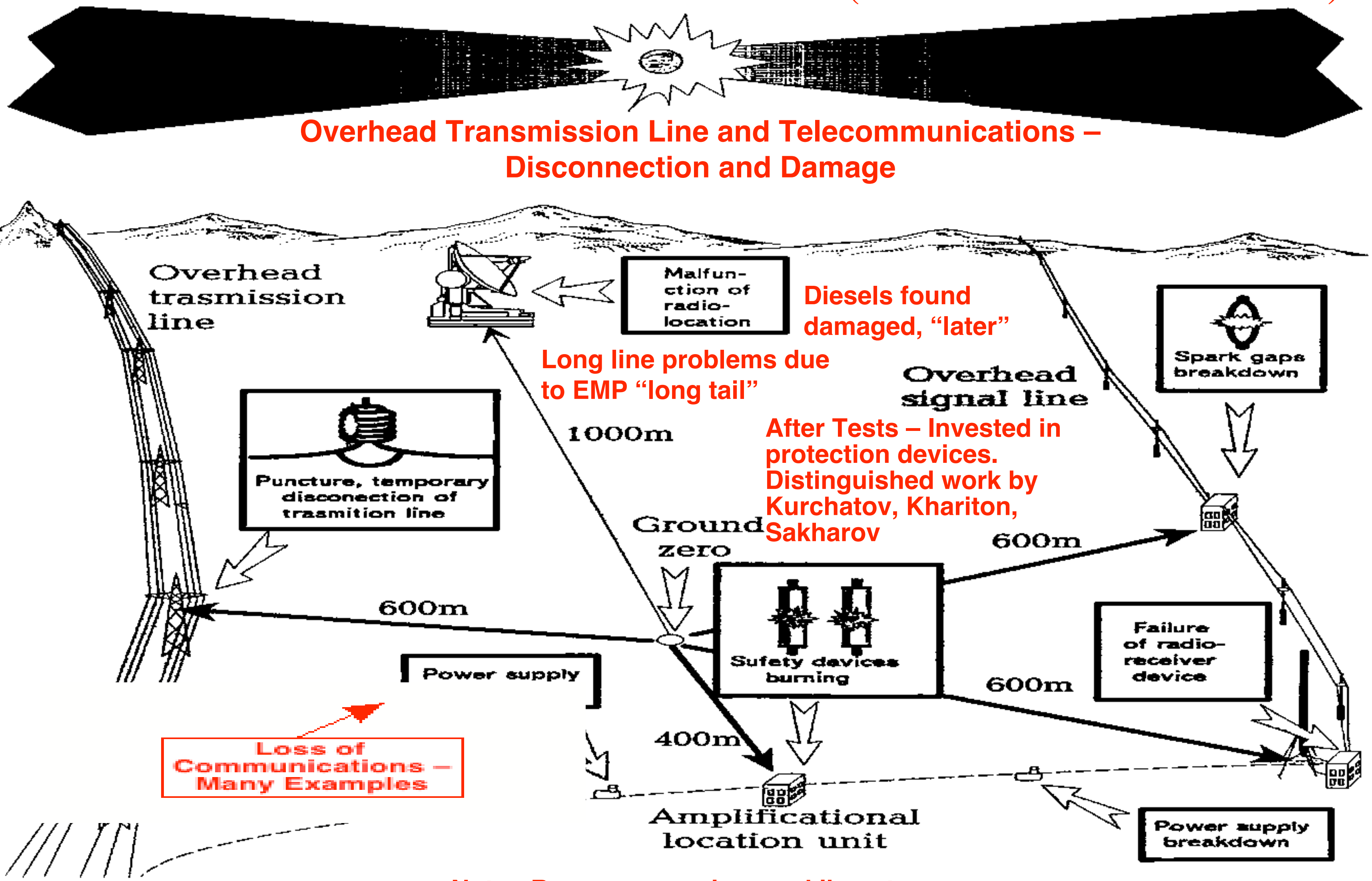
HIGH ALTITUDE ELECTROMAGNETIC PULSE EFFECT (Kazakhstan - October 1962)



Note: Ranges were given as kilometers

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

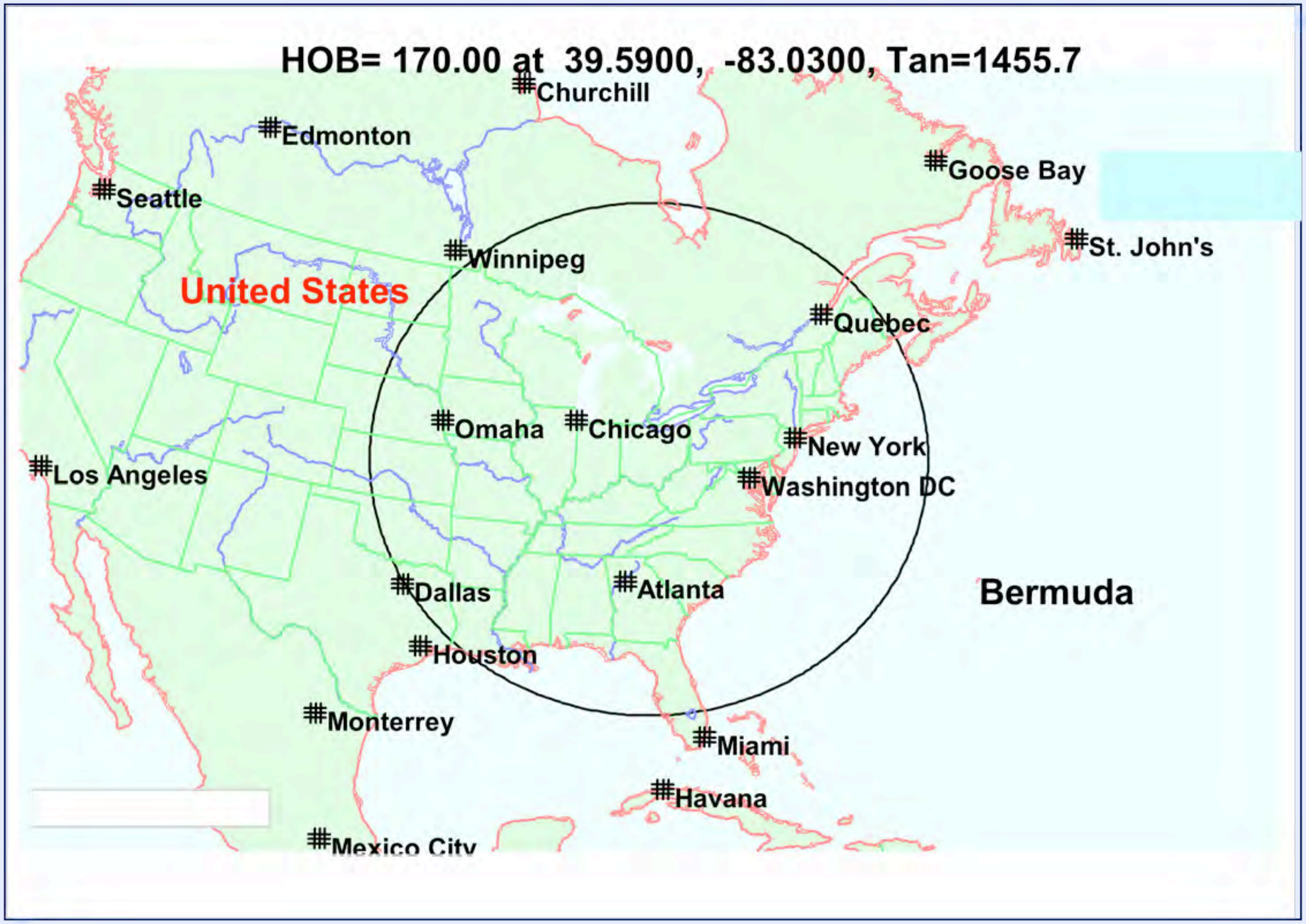
Metatech Power System Analysis

- 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 working with 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
  - Damage risk to HV and EHV transformers identified
  - Time and cost to replace determined
  - Hardening techniques and costs developed

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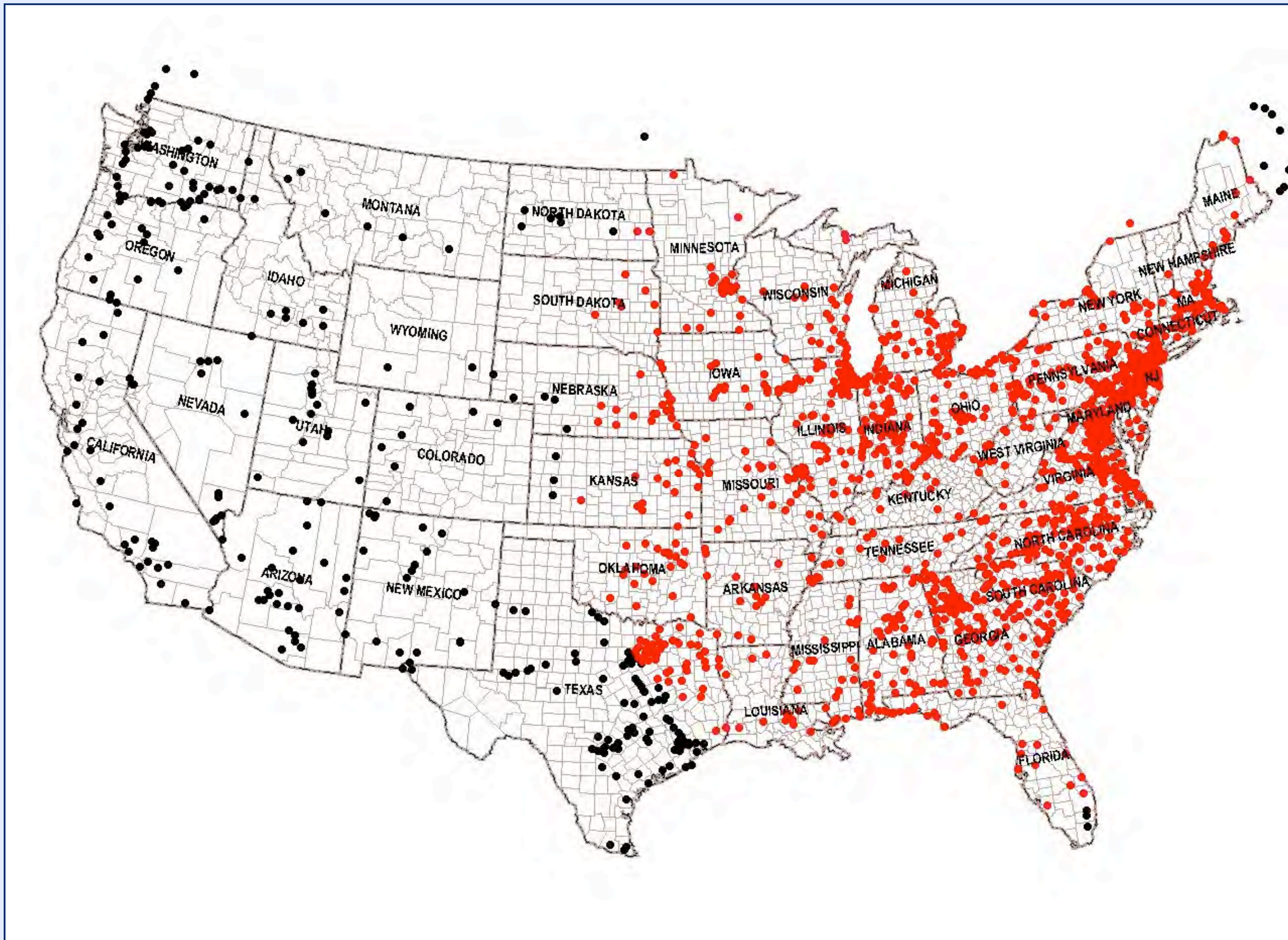
Major HV and EHV Substations Exposed (1765 - 83%)



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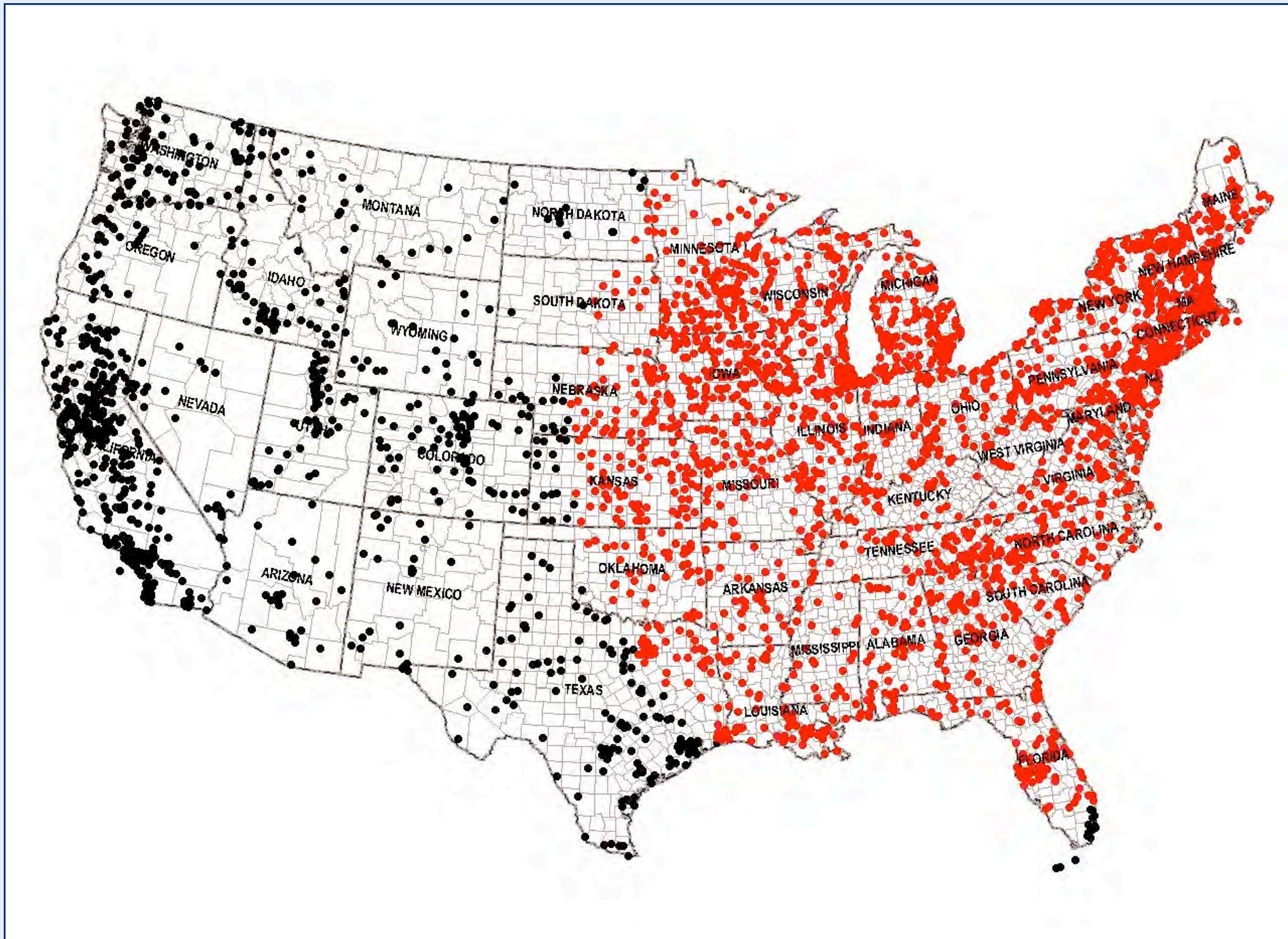
Large Electric Generation Plants Exposed (10,370 - 74%)



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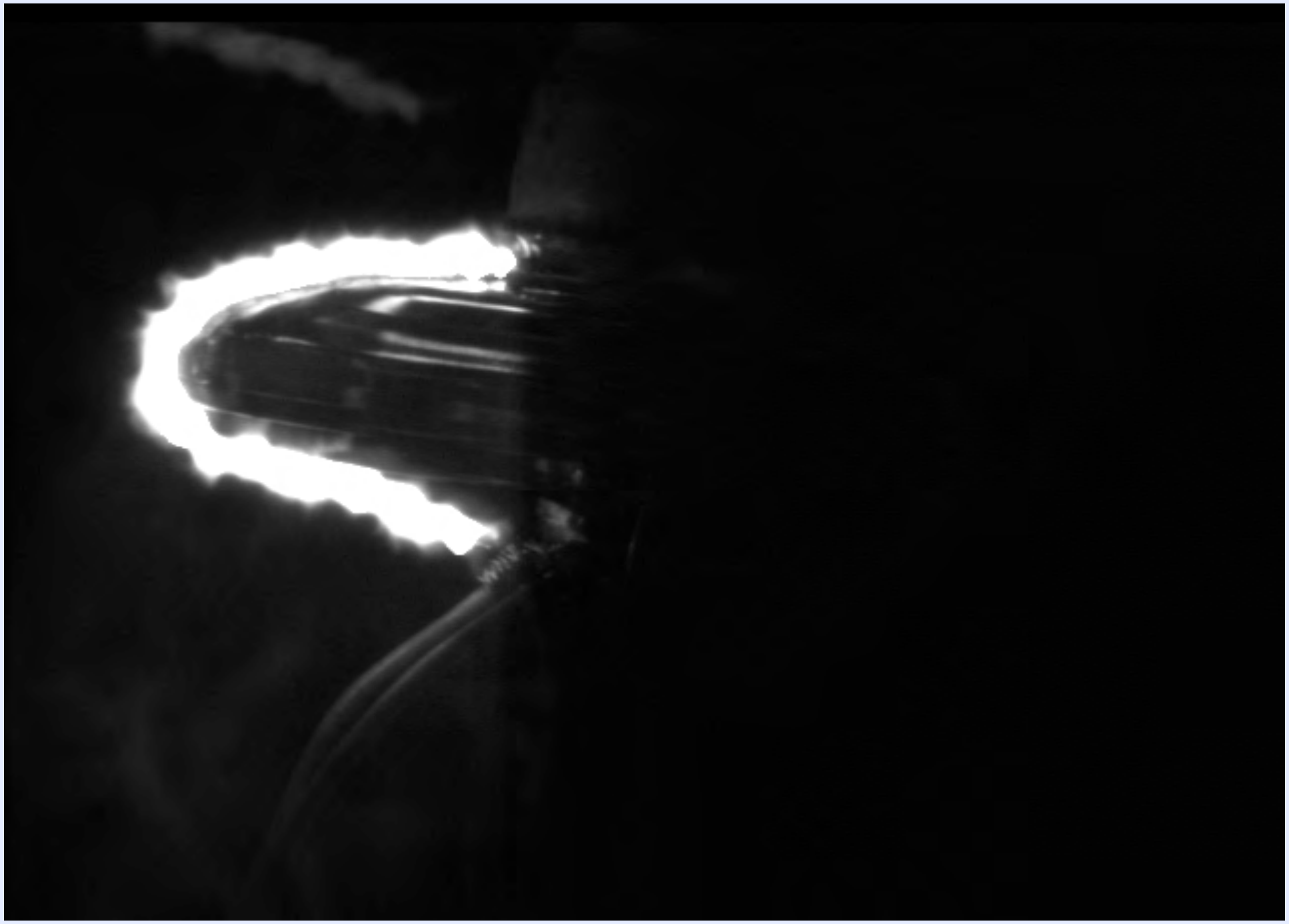
Insulators - Initial stage of electrical arc after 0.5 ms -- power on (E1 HEMP)



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Insulators - Electrical arc -- power on at 2 ms and 1 kA power (E1 HEMP)

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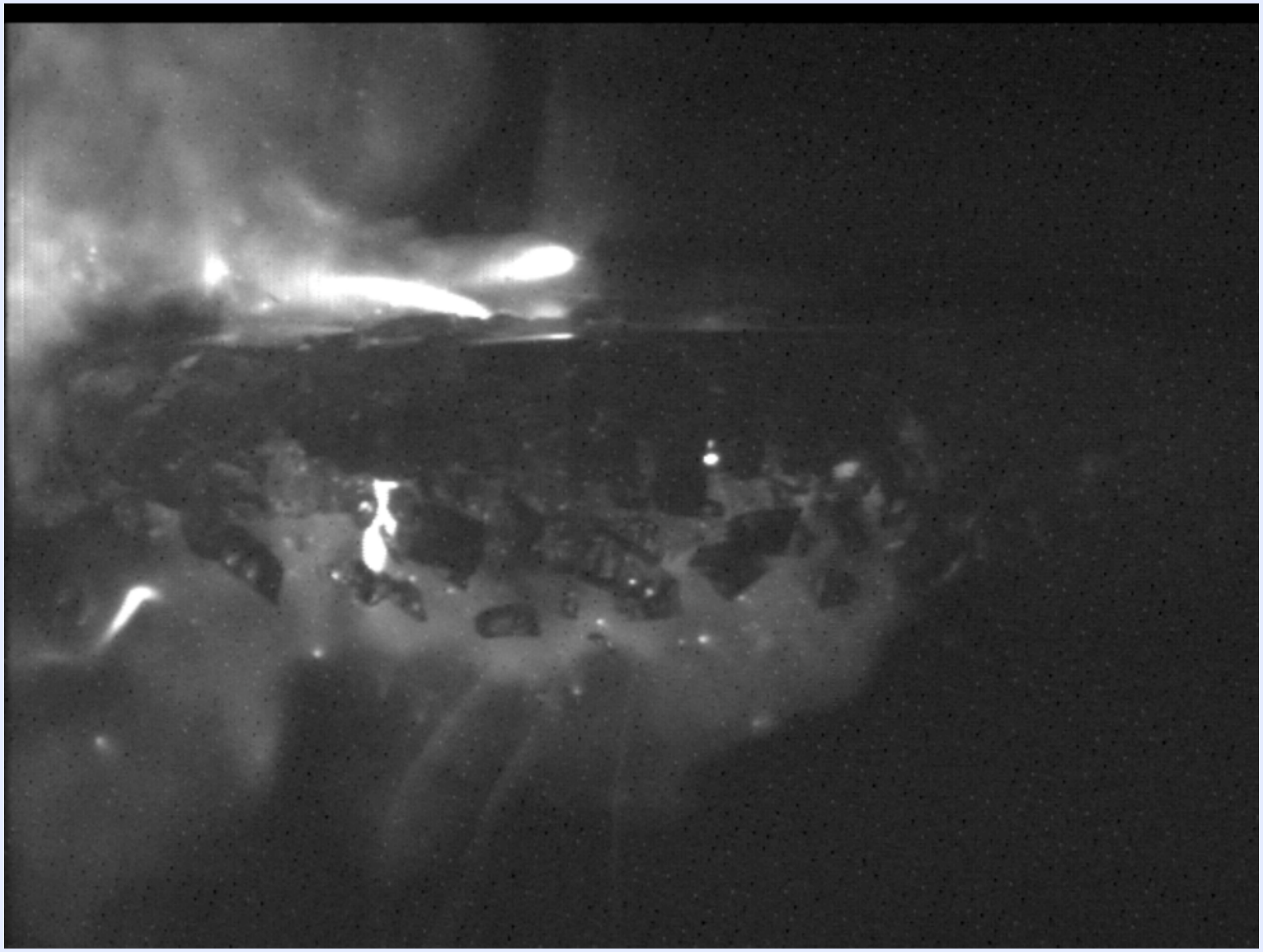
Insulators - Electrical arc -- power on after 10 ms (E1 HEMP)



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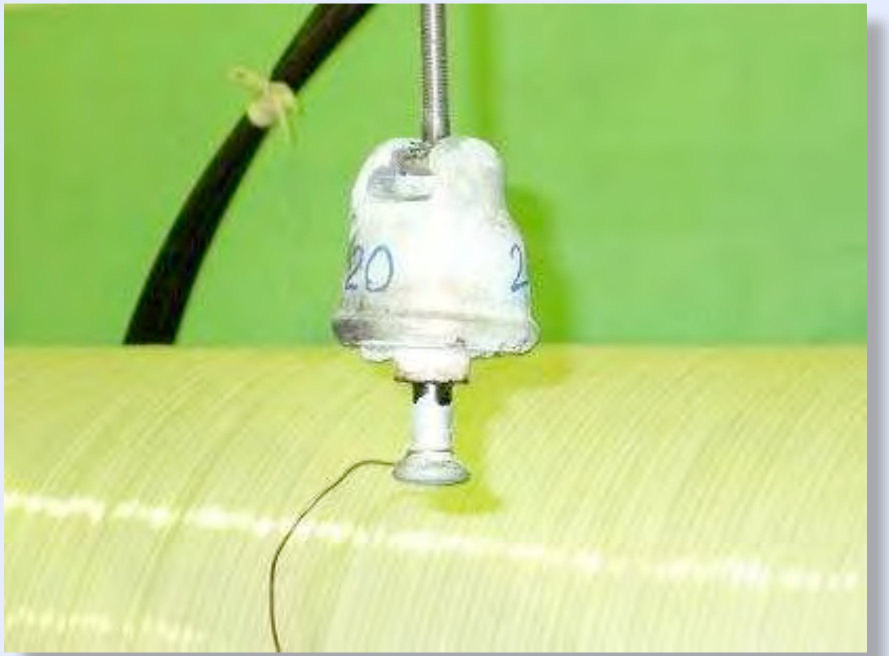
Insulator after Destruction (E1 HEMP)



- Damage to a small percentage of the insulators in the country would likely cause a power grid collapse
  — We need to determine which types and ages of insulators are at risk
  — We need to stockpile spares

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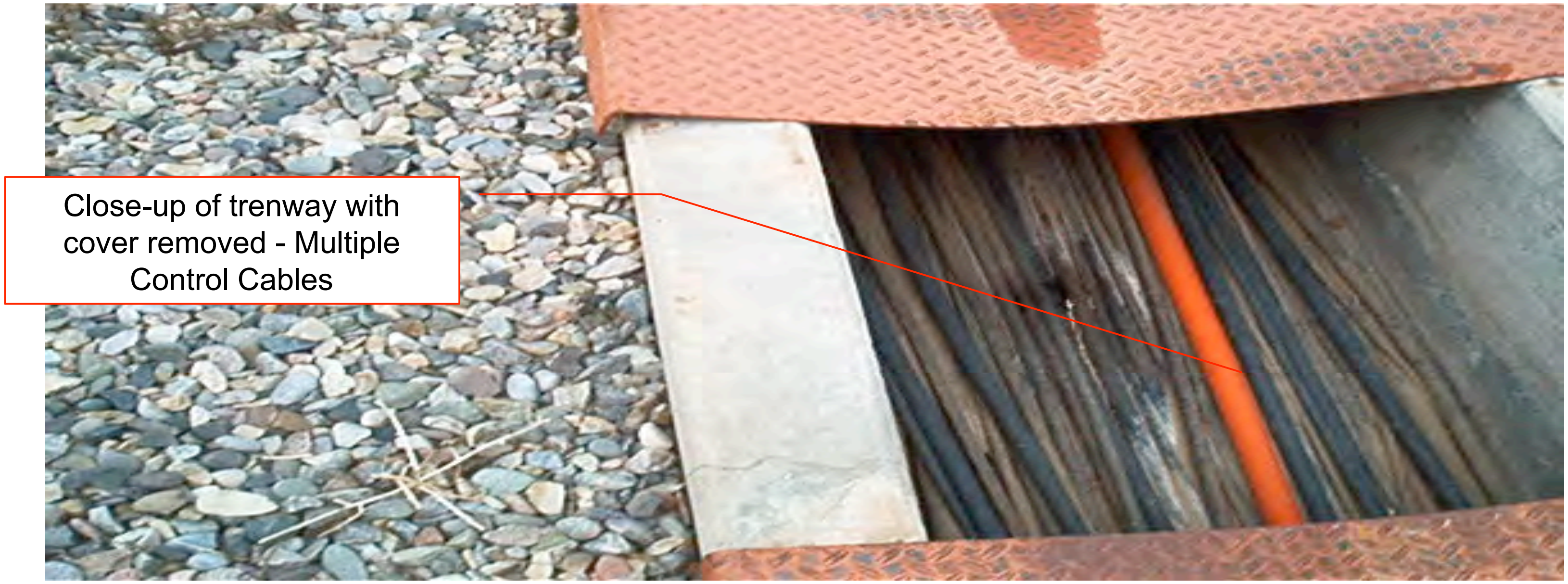
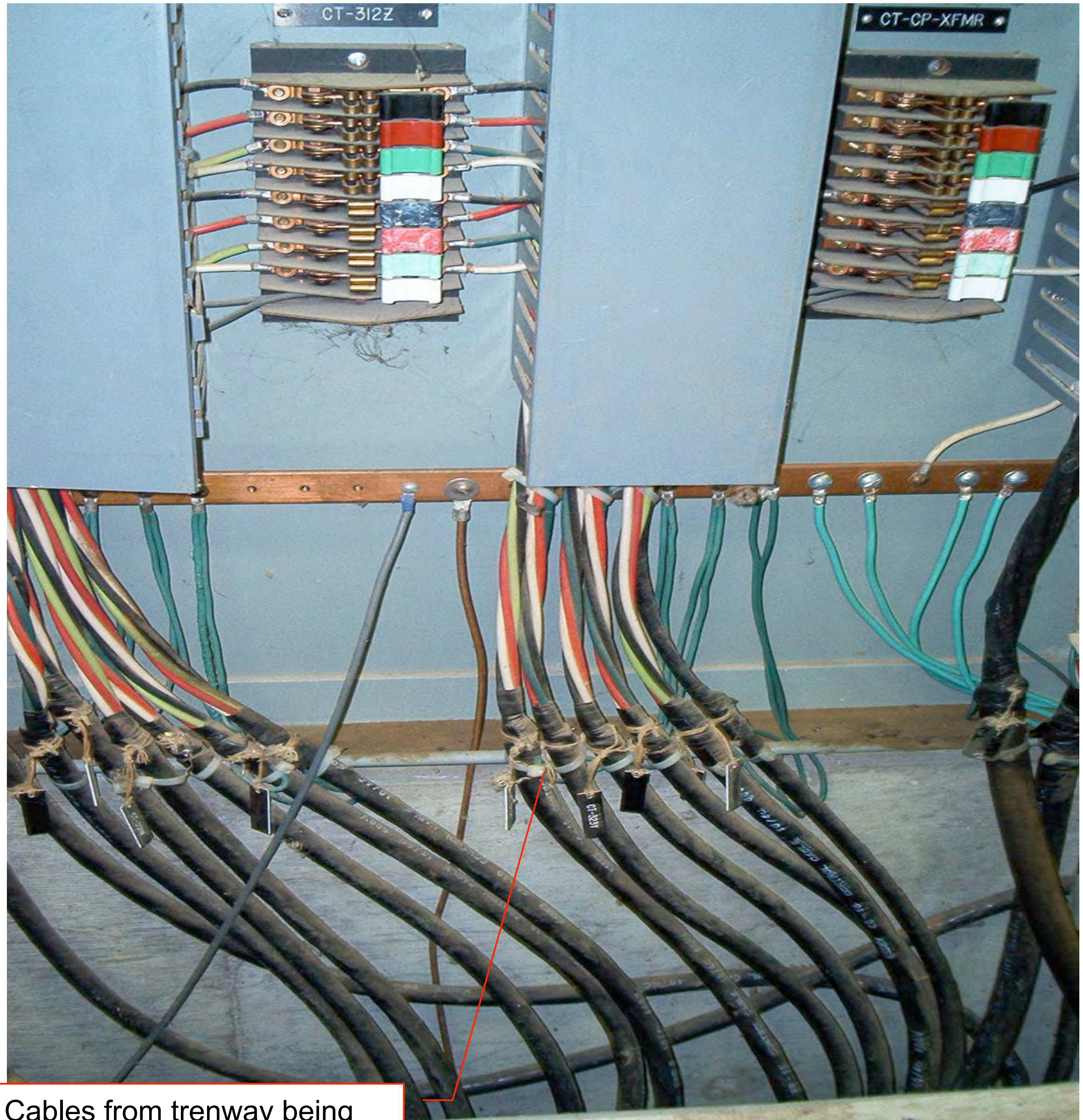
Substation Control Cable Issues

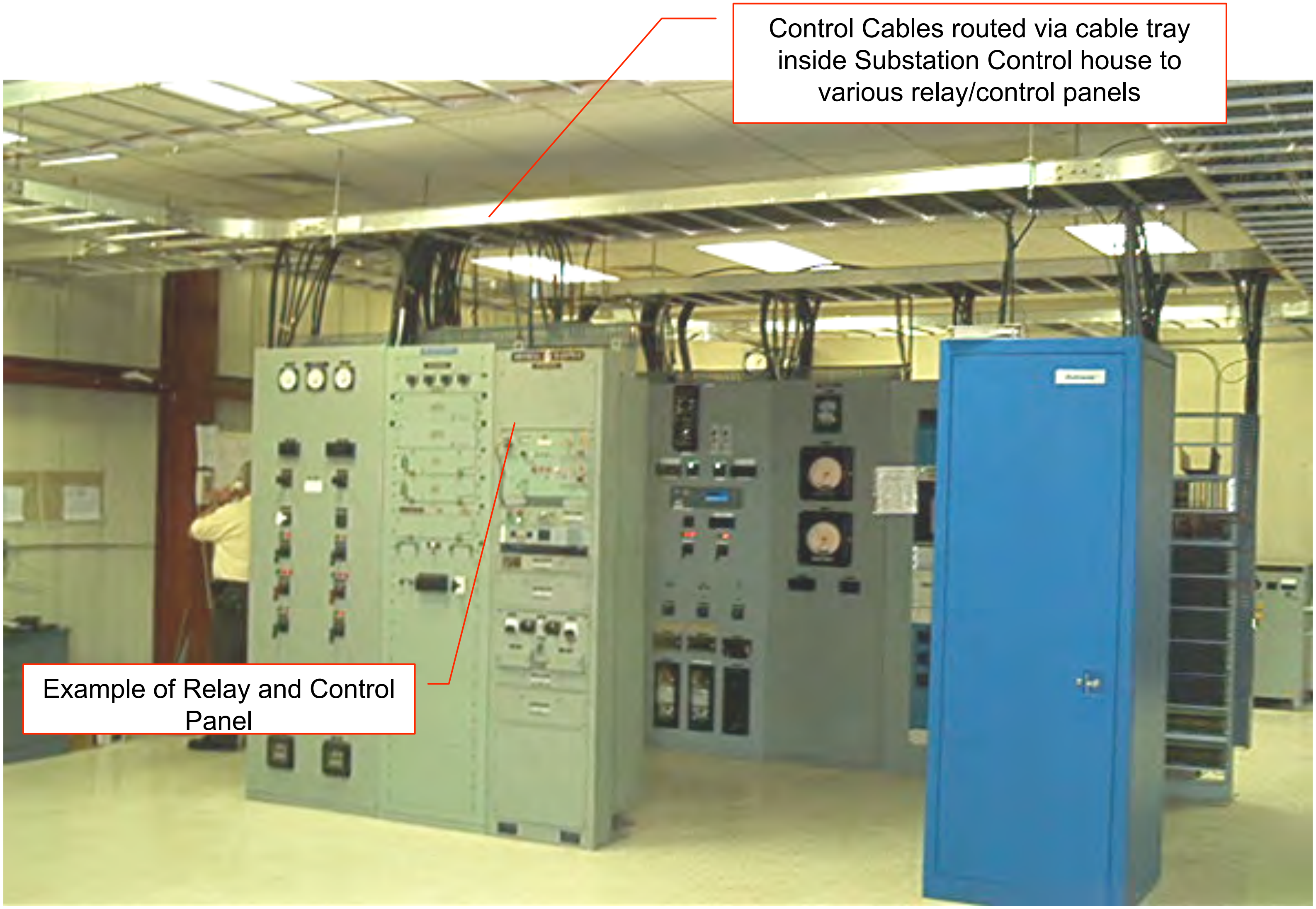
Example of Horizontal exposure of control cables in EHV Substation - Trenway


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

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, 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

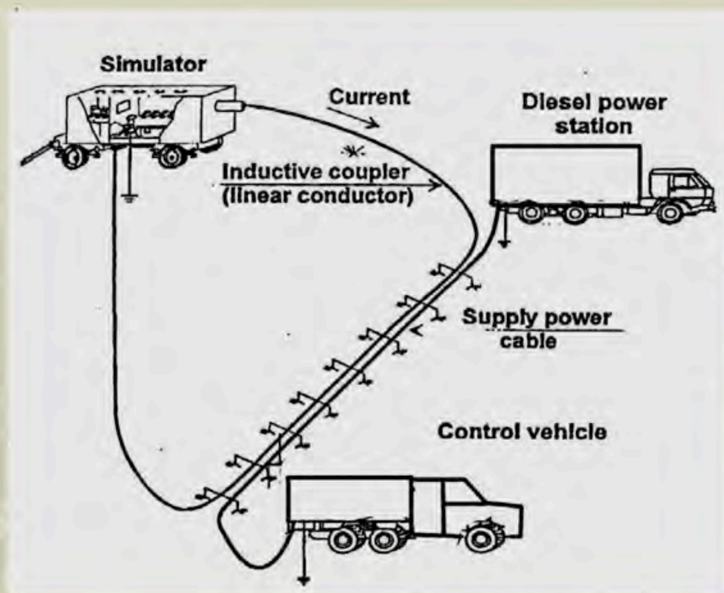
Summary of E1 HEMP Effects on Infrastructure Systems by Russian Scientists

- They reviewed HEMP effects on systems from their «natural» experiments and simulators
- A major conclusion is that systems with cables fail primarily due to the pickup of the EMP fields on the cables (to misquote Pres. Clinton -- it's the cables, stupid -- Radasky)
  - A warning is given that EMP field simulators are not a good way to properly illuminate and test cables
- They indicated that a mobile direct drive simulator was developed in Russia and that power-on testing is crucial to discover failures
- They feel 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

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E1 HEMP Conclusions

- One or a few high-altitude nuclear detonations can produce HEMP, simultaneously, over wide geographical areas (arrival within one power cycle)
- 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, recovery could be prolonged -- months to years
- Costs to the economy range from 1-3 trillion dollars per year

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Overview of Intentional Electromagnetic Interference (IEMI)

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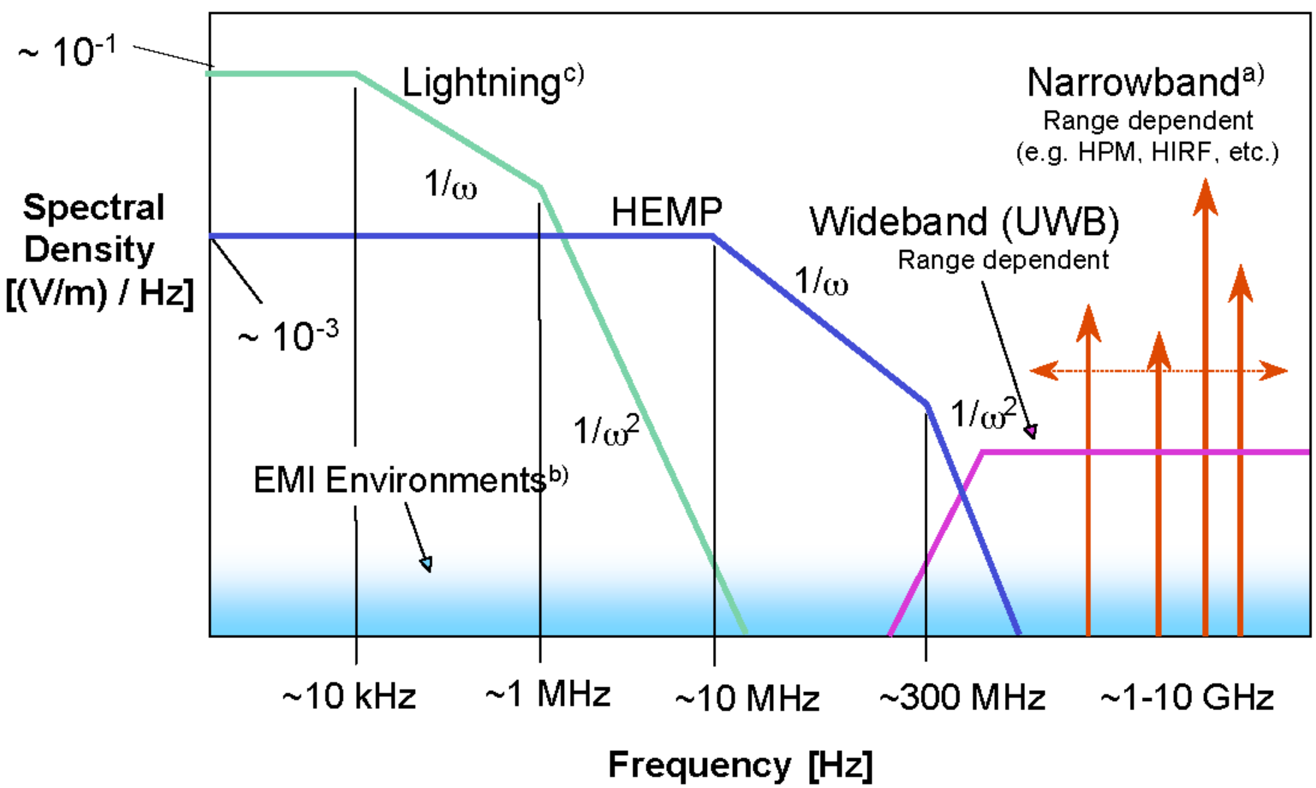
Comparison of Several EM Environments



a) narrow band extending from ~0,5 to ~ 5 GHz
b) not necessarily HPEM
c) significant spectral components up to ~10 MHz depending on range and application

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)

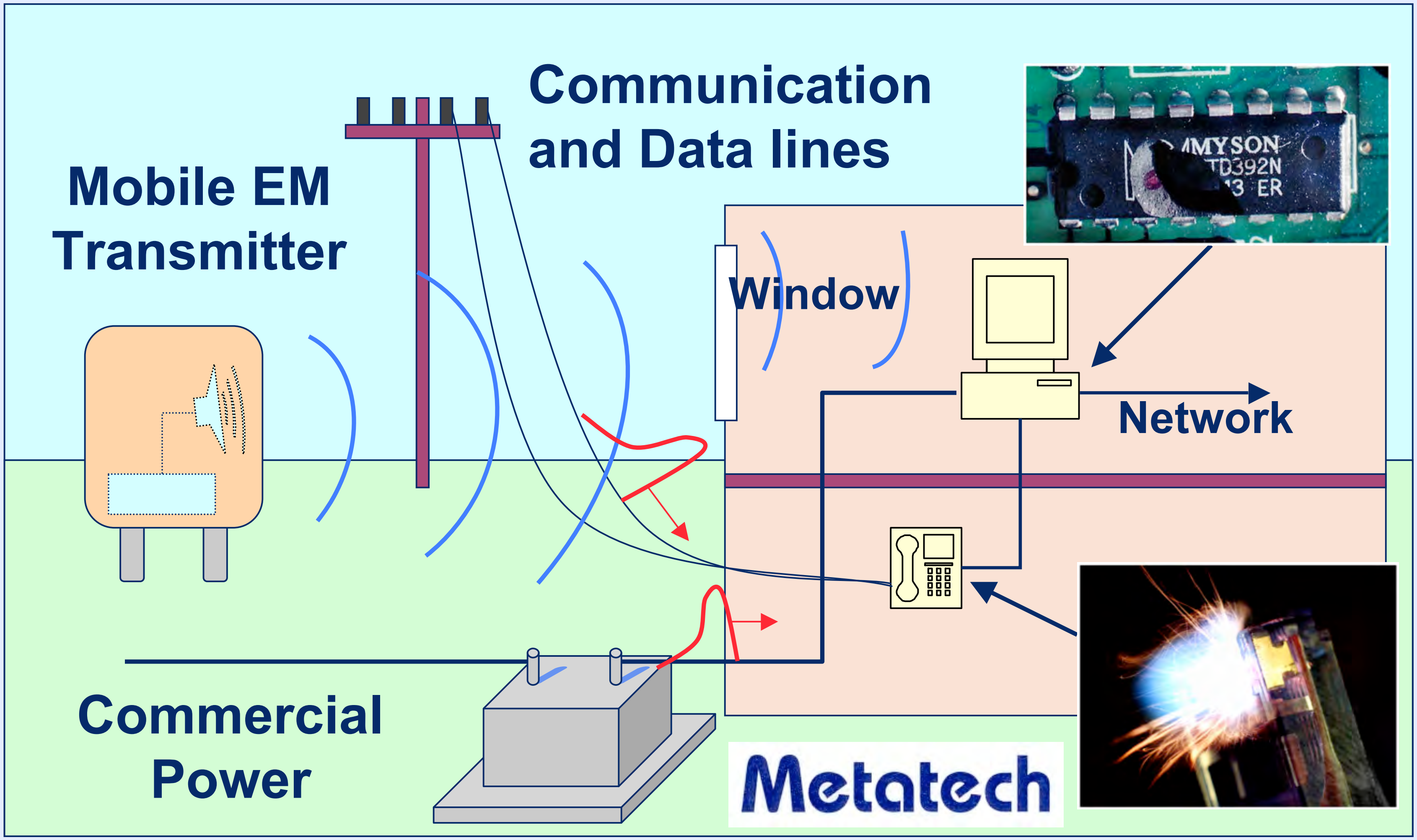
Worldwide Scientific Activity in Protecting Commercial Systems Against IEMI

- **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, protection methods, and monitors**

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 weapons have mainly been designed for military purposes
- The basic technology is not difficult to apply for a qualified engineer
- Commercial electronics equipment is typically not protected against these types of threats
- A new term has been used over the past 10 years to describe this threat and its effects on commercial equipment -- IEMI (Intentional Electromagnetic Interference)

Coupling Paths for Radiated IEMI Fields



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Diehl EM Emitter

- Diehl Munitions Systeme has developed a small interference source (including 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

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

Impacts of IEMI on 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 are also at risk
- Major difference is that the IEMI is a local threat and therefore does not approach the same impact level as E1 HEMP, unless a coordinated attack is performed
- Protection methods for the electronics will be similar for IEMI and E1 HEMP
  - In addition security measures such as physical separation of attack locations and EM monitors can be used for IEMI

Overview of Geomagnetic Storm Impacts on the Power Grid

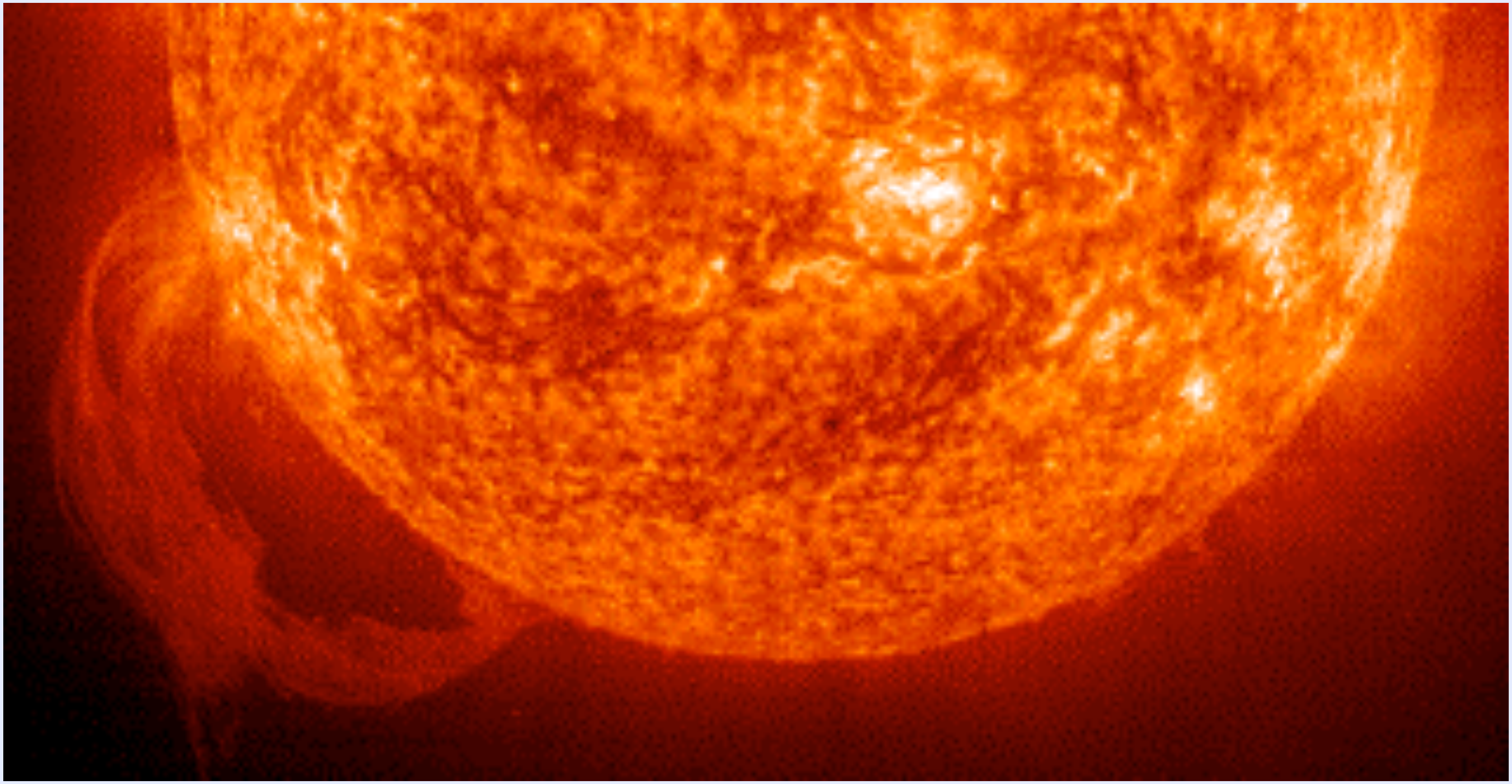
Introduction

- Over the past 21 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
- 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

A Review of Power Grid Vulnerability to GIC Events

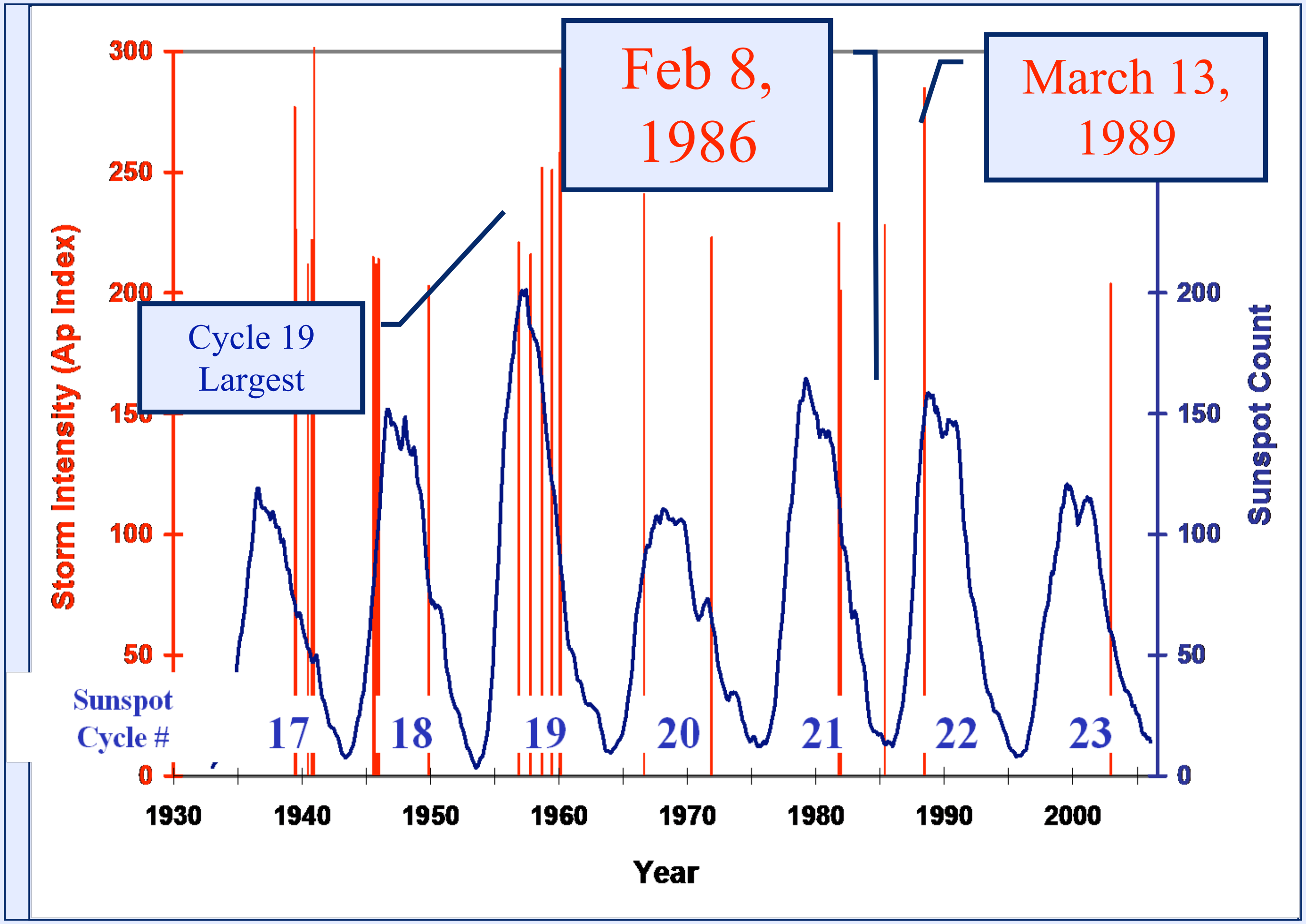
- Geomagnetic storms are disturbances in the Earth's normally quiescent geomagnetic field caused by intense solar activity
- A rapidly changing geomagnetic field over large regions will induce Geomagnetically-Induced Currents (i.e. GIC, a quasi-DC current) to flow in the interconnected HV/EHV/UHV bulk 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



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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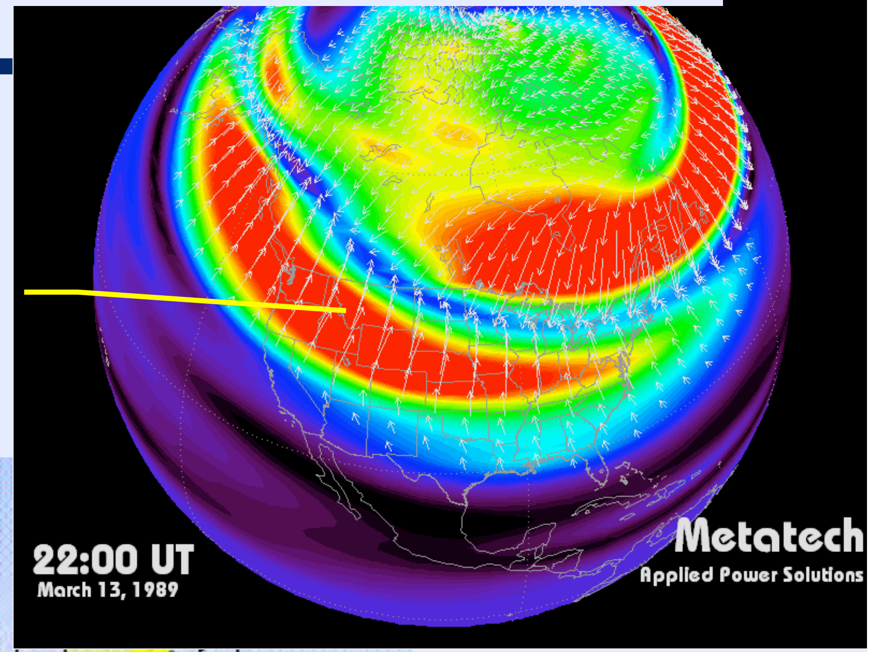
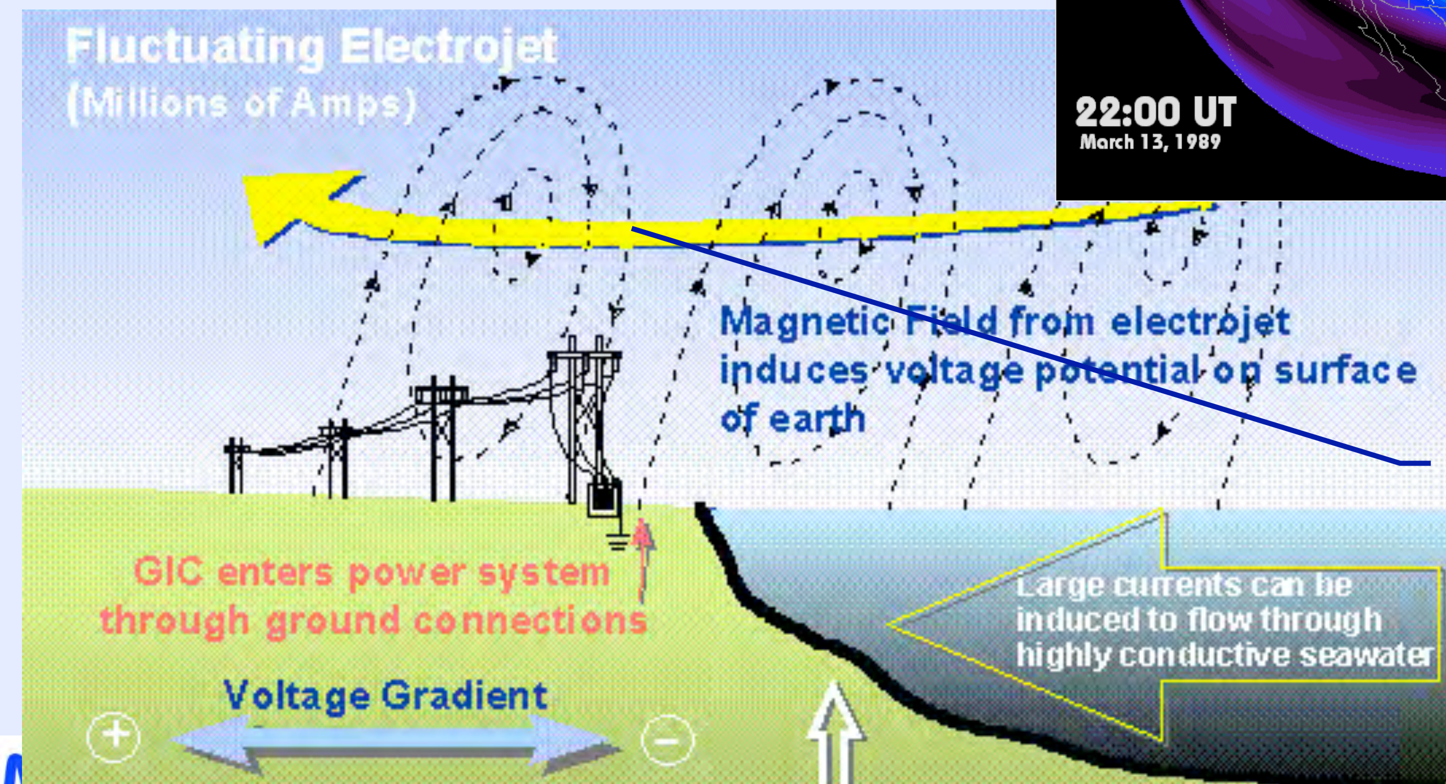
Geomagnetic Storms and Large Power Grids

Storms have Continent-Wide Footprints

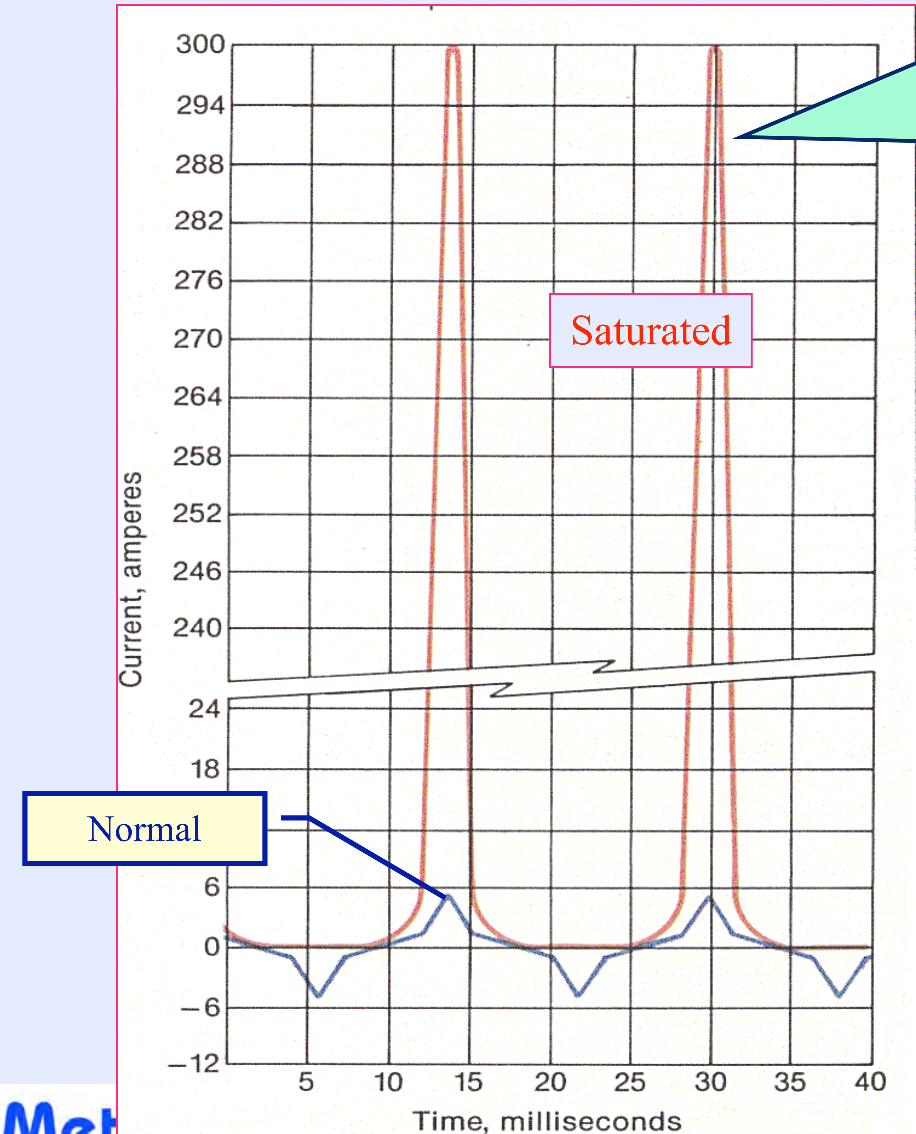




Field Disturbances from Electrojet Current Couple to Power Systems

GIC in Transformers

The Root Cause of All Power Grid Problems

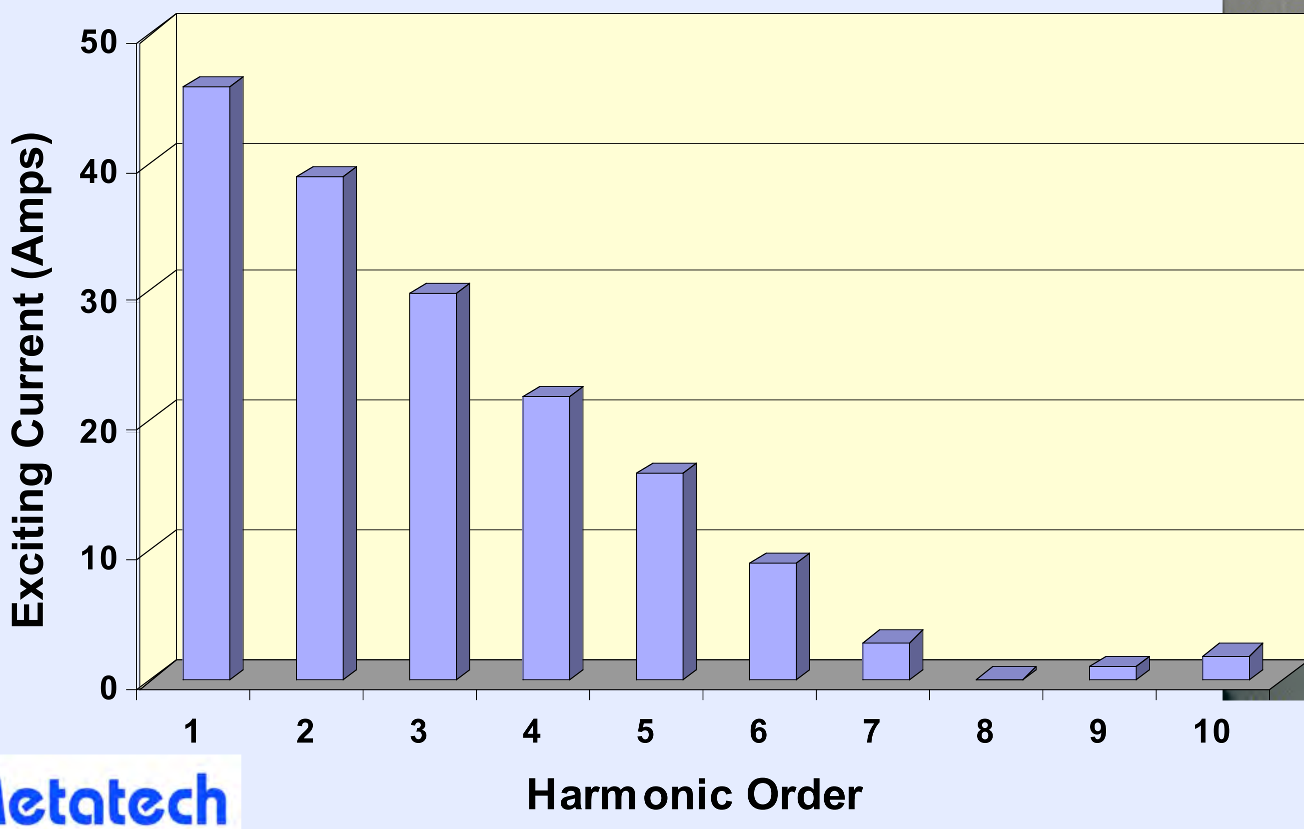


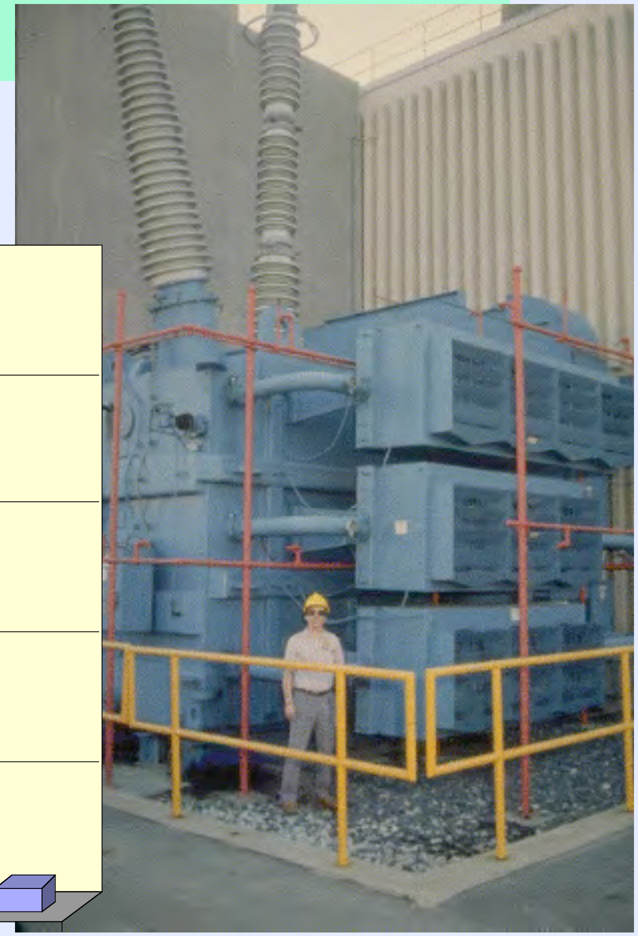
- Transformers easily *Saturate* with even minor levels of GIC
- Storms cause problems in hundreds of transformers at the same time

GIC Caused Transformer Saturation Injects Harmonics

Harmonics can create other distortion-related problems and contingencies in the network

Transformer Harmonics





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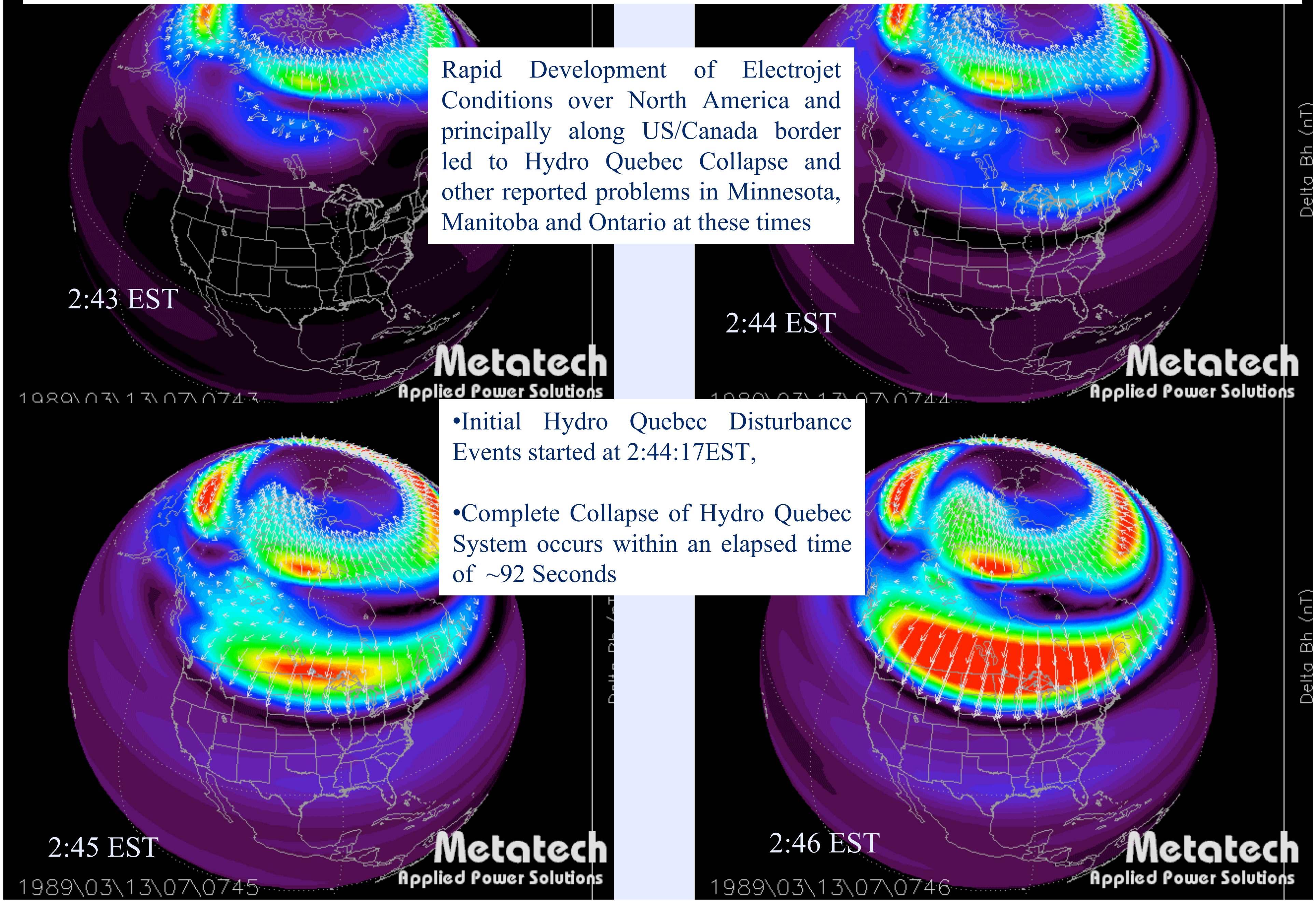
March 13, 1989 – 4 Minutes of a Superstorm

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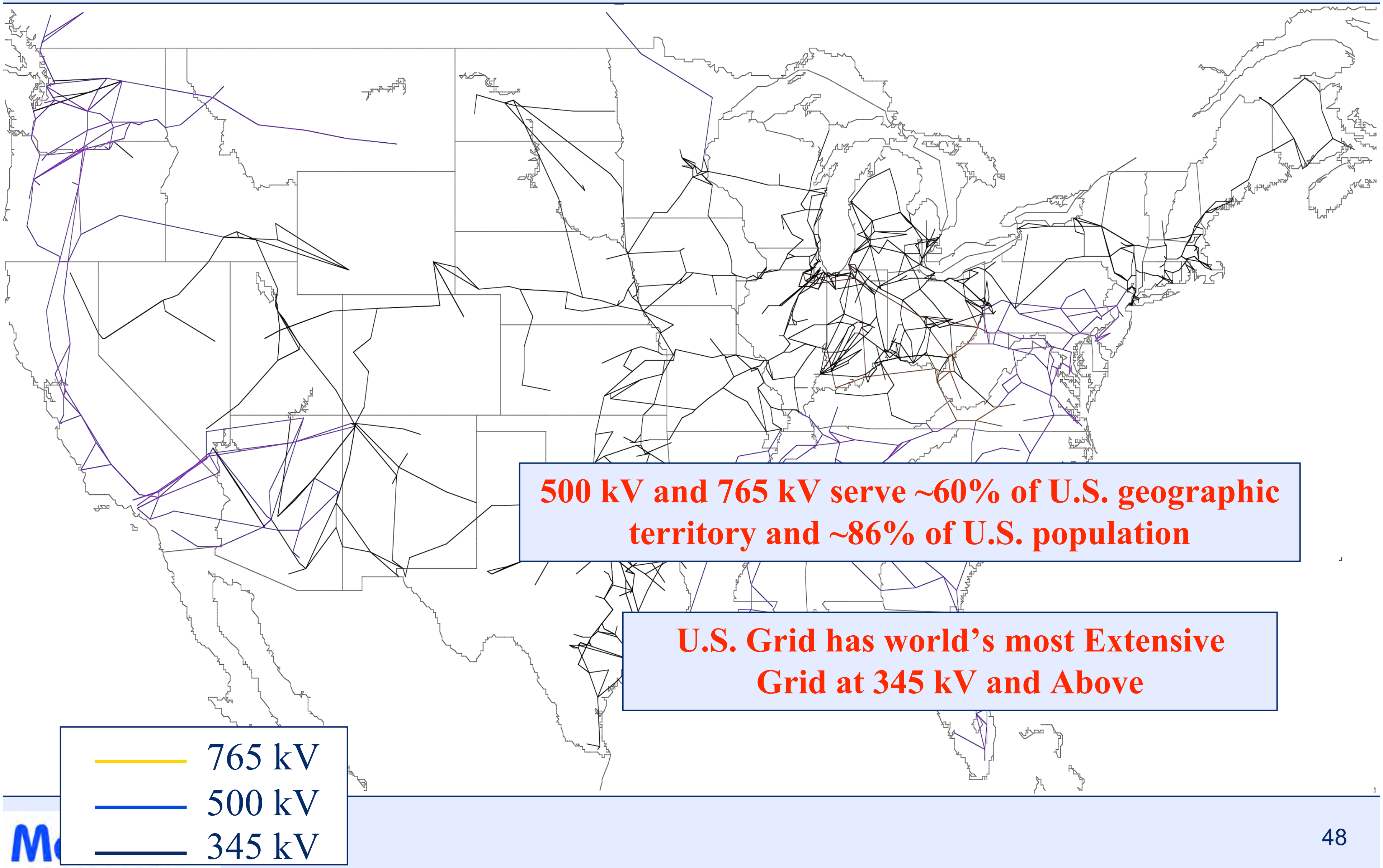
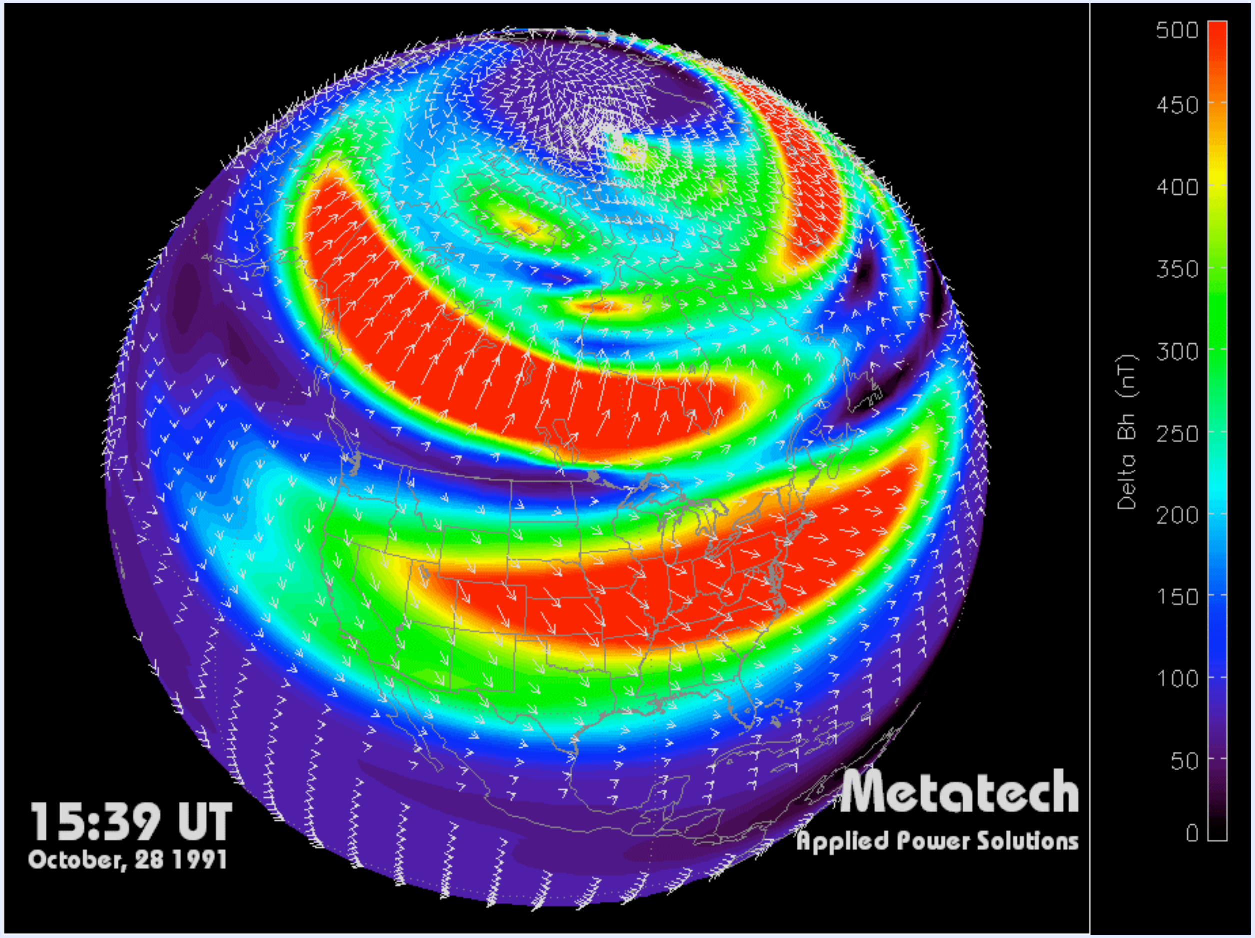
U.S. High-Voltage Transmission Network Model for GIC Simulation



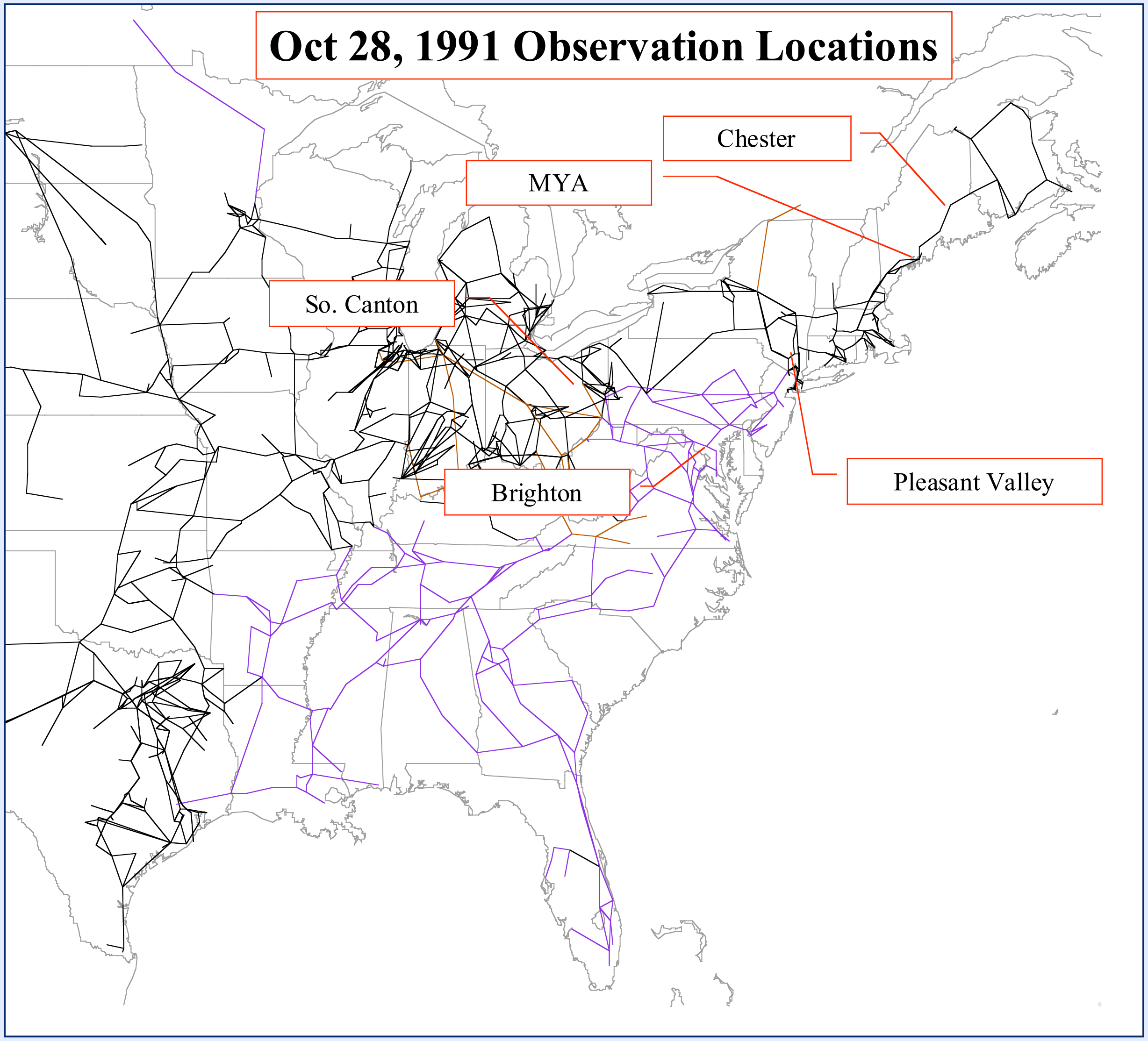
500 kV and 765 kV serve ~60% of U.S. geographic territory and ~86% of U.S. population

U.S. Grid has world's most Extensive Grid at 345 kV and Above

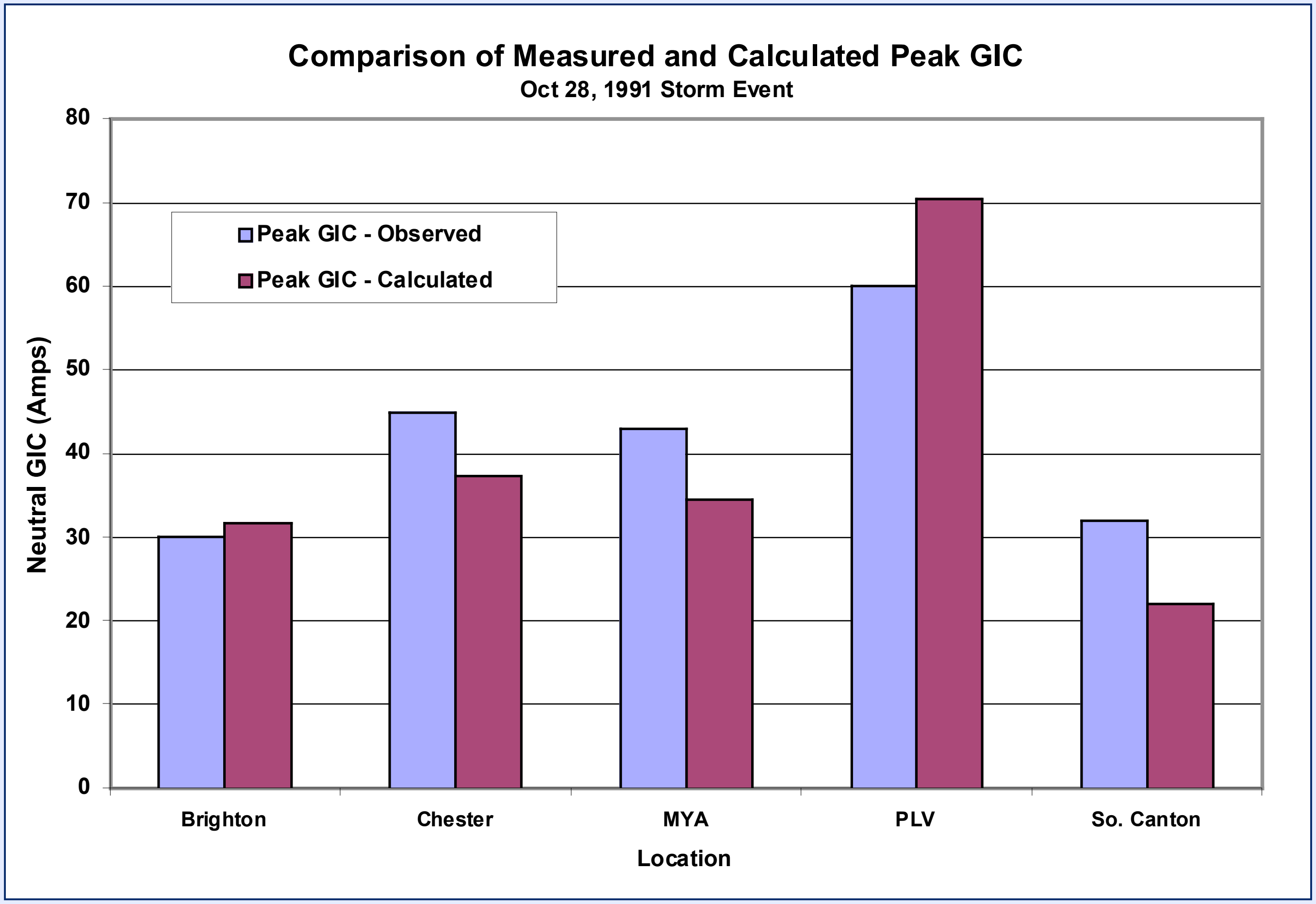
Geomagnetic Disturbance Conditions 15:39 UT on Oct 28, 1991



Locations of GIC Observations on Oct 28, 1991



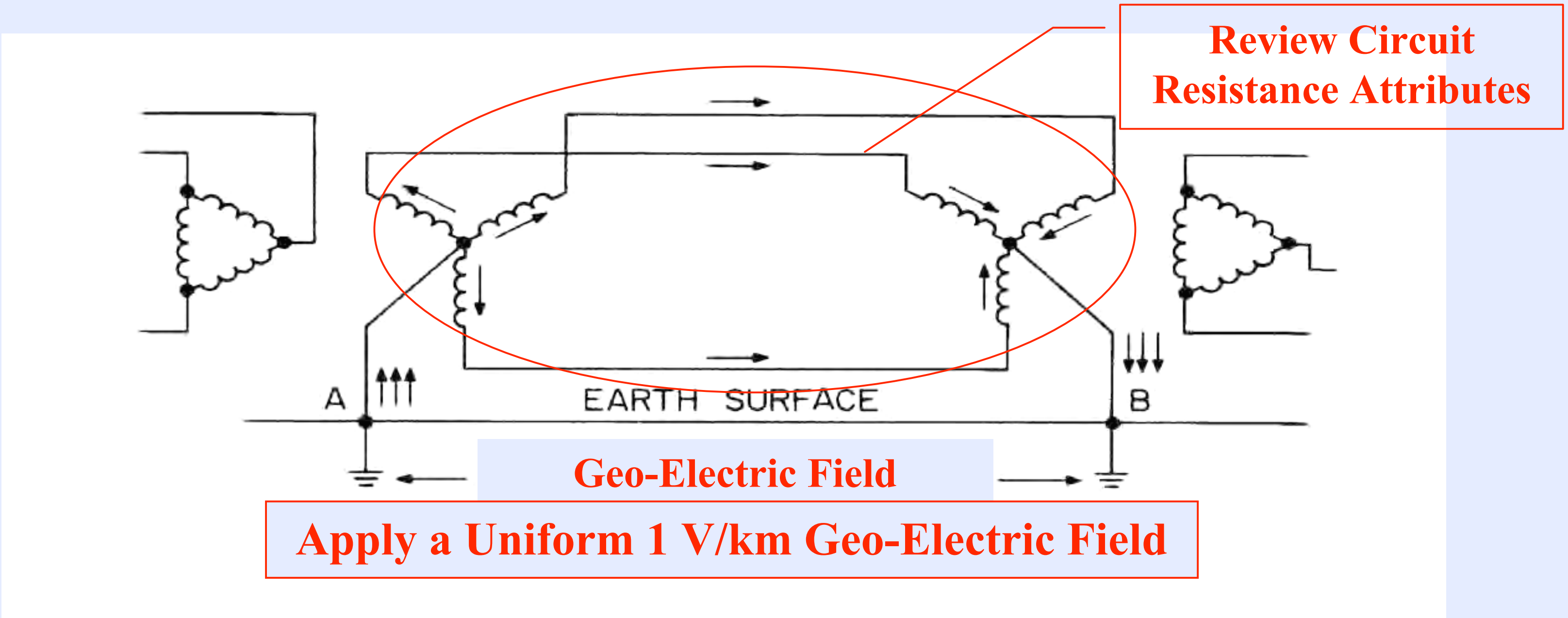
Code/Data Peak GIC Comparisons



Impacts of Grid Voltage Level

- Experience has indicated that the largest measured currents occur in the highest voltage U.S. grids
  - Modeling has confirmed this conclusion
- The next few charts illustrate a simple analytic calculation that examines the specific reasons for this trend
  - Begin with a 100 km transmission line
  - Induced E-field assumed to be 1 V/km
  - Typical resistances for different operating voltage line resistances and transformer resistances are collected
  - Current flow trend is computed

Power Grid Design Trends and GIC Risk Factor



A Simple 100 km Transmission Line and Transformer Connections to Ground
Illustrates GIC Flow Circuit Principles for More Complex Network Topologies

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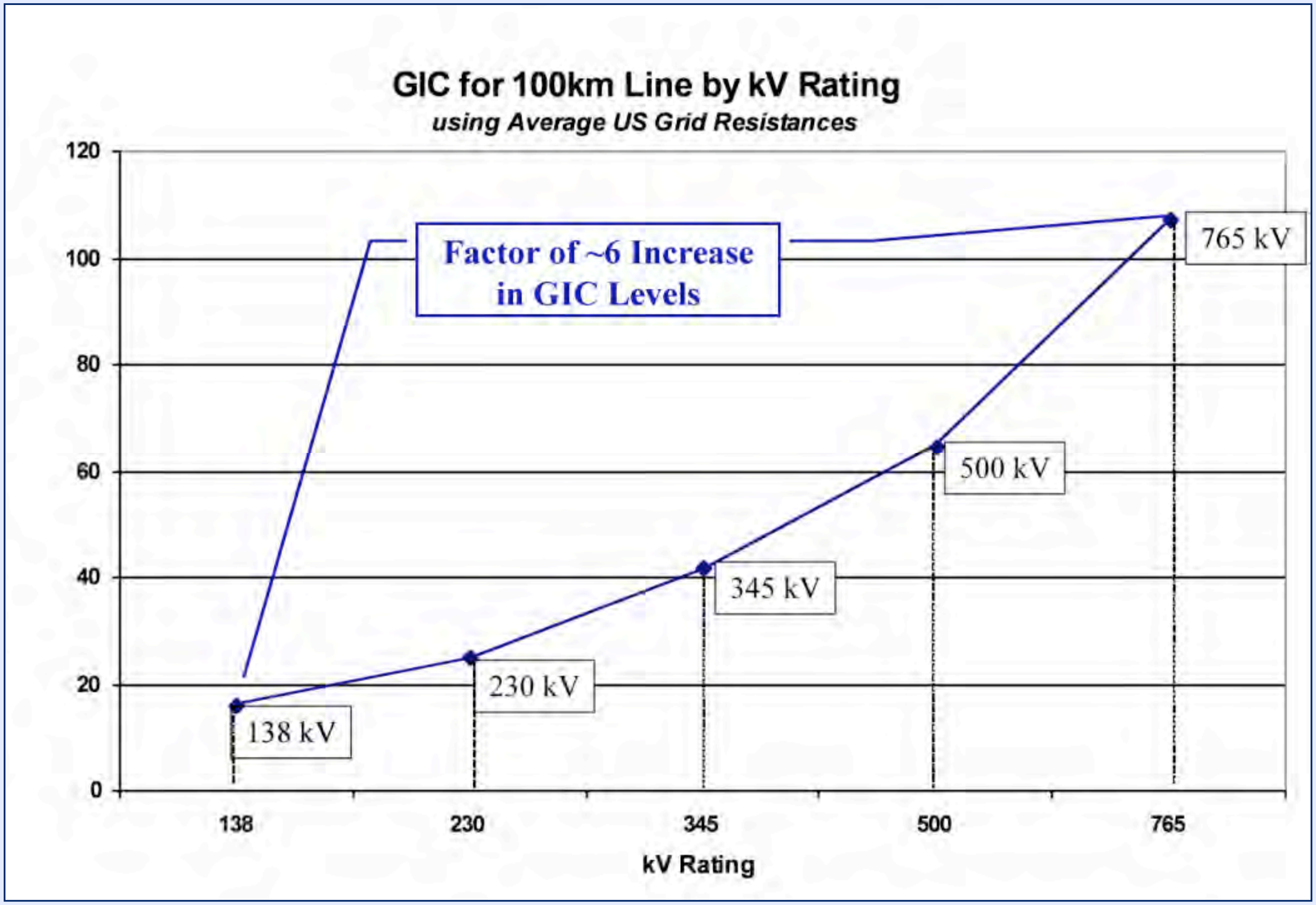
GIC Risk Factor – kV Rating Design (amps/phase)



Trend -The Higher the kV Rating – the More Efficient the Antenna

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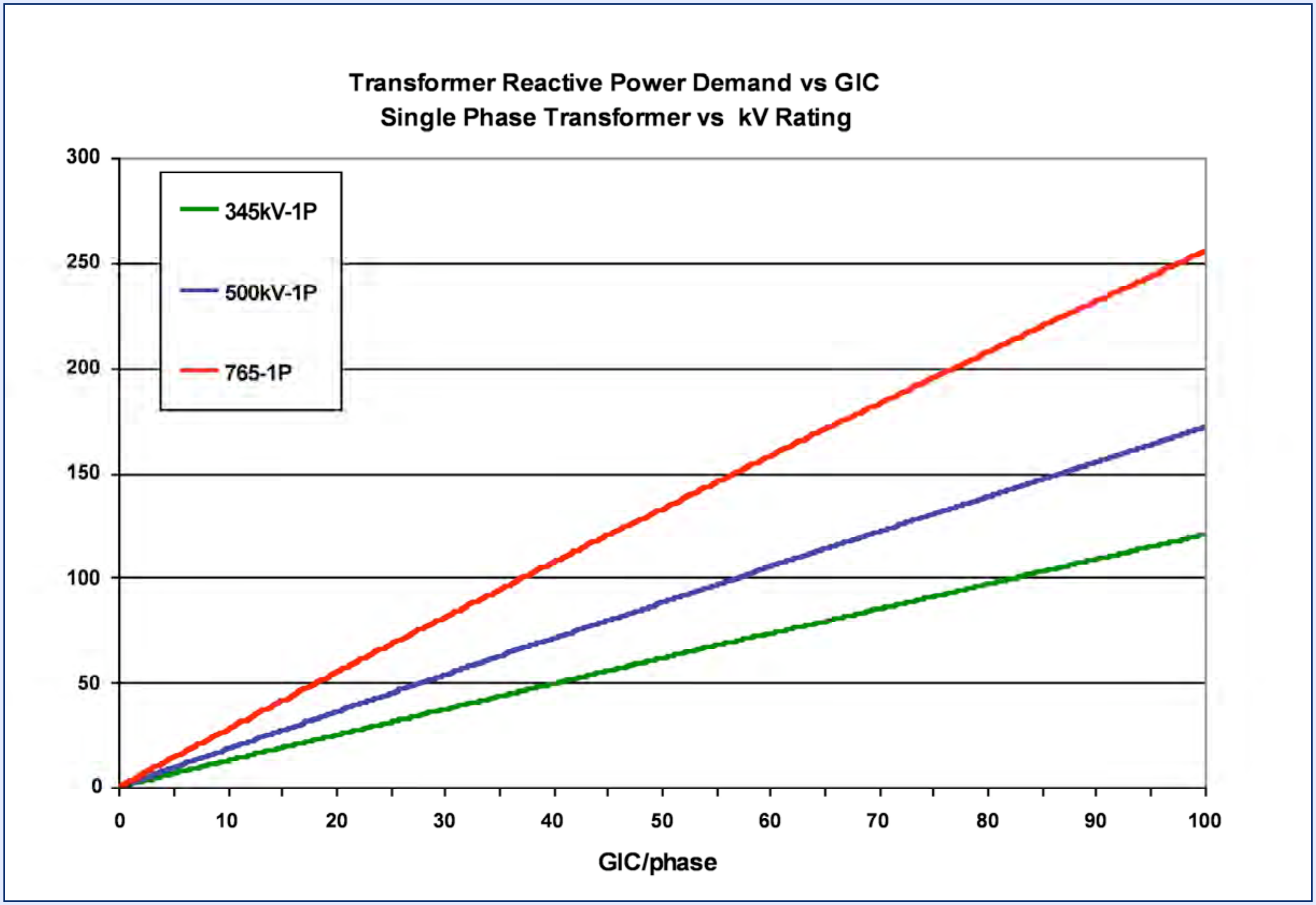
GIC Risk Factor – Reactive Demand (MVAR)



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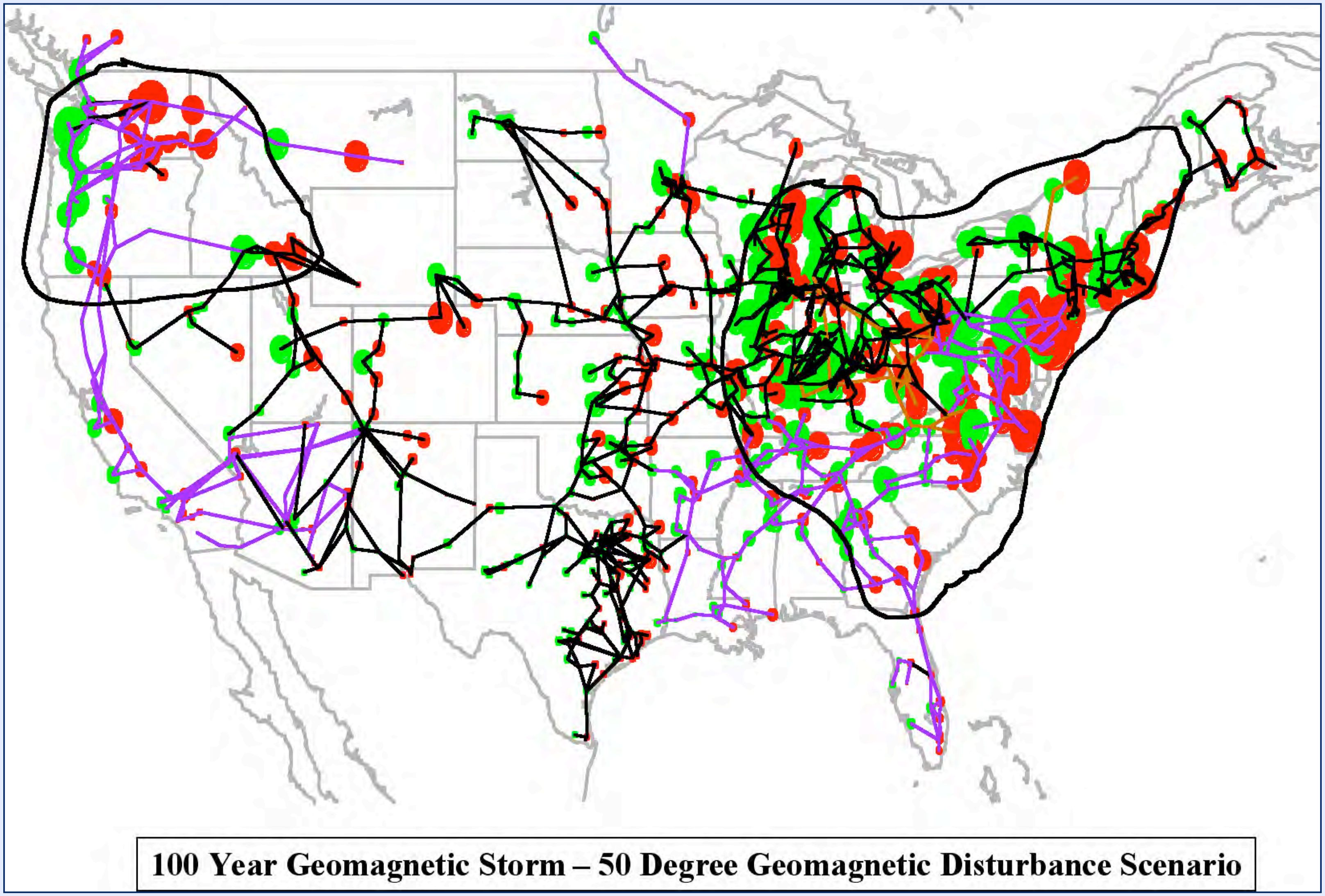
Summary of Grid Voltage Impacts

- Comparing the induced GICs in different voltage systems, the average increase in current is about a factor of 6 between 138 kV and 765 kV
  - Between 345 kV and 765 kV, the factor is ~x2.5
- Given the voltage of the transformers and for single phase units, the reactive power increase between 345 kV and 765 kV is about x2.0
  - The net GIC + reactive power impact between 345 kV and 765 kV is ~x5.0
- This trend is expected to continue for voltages at or above 1 MV

Impact of a Large (4800 nT/min) Geomagnetic Storm over the US



Protection!

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**
  - **Hospitals need protection from MRI machines**
  - **Protection against cellular phones (major initiative that continues today -- gas stove example)**
- **These EM threats are recognized and dealt with as they occur**
- **Not as easy for low probability events to evaluate and then to fix the problem**
  - **For the power grid, the impact would be very high**

Protection Methodology

- Basic approach
  - — Analyze the EM threat (time and frequency spectrum)
  - — Determine sensitivity of electronics and transformers
  - — Develop protection approach to reduce transients to acceptable levels
    - EM shielding for fields
    - Cable penetration protection (filters, surge arresters, etc.)
    - Neutral protection for large transformers
    - With few exceptions the protective elements are available
  - — Develop test methods to validate hardening
  - — Develop standards to replicate process over and over in a cost effective manner (IEC, IEEE, Electric Code, etc.)

- Success in the process requires experience with EM transients, which is already established in the EMC discipline (worldwide)
  - — Engineers with an EM education are needed
  - — IEEE participation is very important (EMC, PES, APS)
  - — Familiarity with major EMC, HEMP, and IEMI standards
  - — Development of protection elements that are consistent with the threat

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
  - —IEC SC 77C was formed in 1991
- 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

20 Publications Produced by IEC SC 77C

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
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
61000-6- (Generic Standards)	-6 GENERIC STANDARD FOR HEMP IMMUNITY

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IEC Standards Conclusions

- IEC SC 77C has been very active for 20 years in producing standards and other publications to deal with the protection of civil systems from HEMP and IEMI
- SC 77C publications are basic standards that form “building blocks” to be applied to electronic equipment
  - — 20 publications have been produced
  - — 2 additional publications are being maintained
- SC 77C is working with the ITU-T to coordinate the HEMP and IEMI protection of telecommunications centers
- SC 77C is coordinating with CIGRE on the protection of HV substation controls from IEMI
- These standards are the best place to start to understand the threats and to develop protection methods for commercial electronic systems

What's New - 1?

- Over the past 18 months the Federal Energy Regulatory Commission (FERC) has been examining these EM threats to the U.S. power grid and possible protection methods
- On 21 July 2009 the U.S. House held a hearing to examine the need to protect the U.S. power grid against these EM threats
- In November 2009 and March 2010 the North American Electric Reliability Corporation (NERC) held workshops to inform industry about high impact, low frequency (HILF) threats to the power grid

What's New - 2?

- The House Energy and Commerce Committee passed the "Grid Reliability and Infrastructure Defense Act" (HR 5026) by a vote of 47-0 on 15 April 2010
- Final House vote was unanimous on 9 June 2010
  - Gives FERC the authority to address imminent threats to the electric grid with emergency orders
  - FERC is directed to address longer-term grid vulnerabilities with standards written or approved by FERC
  - The defense department has agreed that this bill is critical to our national security
- Senate Energy and Natural Resources chose instead to push a "clean energy" bill, S. 1462 which did not include many of the parts of the House bill
- Due to the press of time before the election (or during the lame duck session) it was not possible to resolve the two bills, so it appears the process will begin again in the current Congress

What's New - 3?

- Smart Grid!

- All of the discussion in this briefing, and the work of the EMP Commission, the National Academy of Sciences (Space Weather), NERC and FERC deal with the threat of high power EM threats to the existing power grid

- Smart Grid includes many concepts including
  - Additional monitoring on the transmission and distribution grids
  - Use of more variable power generators (e.g. wind, solar) that requires more active control of generation
  - Smart meters
  - Demand response (including domestic appliance controls)
  - New communication systems to accommodate real time data transfers

- SGIP (Smart Grid Interoperability Panel) has formed an EMC working group to consider EMC immunity aspects and also to consider HPEM threats