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EMP Risks and Mitigation

Presented to the
Electromagnetic Pulse (EMP) Seminar
Regional Resiliency Assessment Project (RRAP)
28 May 2015

Note: This briefing does not present a formalized DHS position regarding EMP, Solar Superstorms, and RF Weapons. It does consolidate some subject matter expert advice from government and industry regarding EMP risks and mitigation.

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Background: What is EMP?

Significant electromagnetic pulse (EMP) threats occur when:

1. A nuclear weapon is detonated
2. An extreme solar storm occurs
3. A non-nuclear EMP (Radio Frequency) weapon is used

Three major types of nuclear EMP

1. Source Region EMP (SREMP) - observed since our first nuclear test
   - Mainly a problem with surface detonations
   - Can disrupt power and communications throughout an entire city/region
   - Physics are well understood/modeled, but effects are widely misunderstood
2. High Altitude EMP (HEMP) – from balloon or missile nuclear burst
   - 1 burst can disrupt U.S. power/communications over many states or continent
   - May take months or years to repair damage
   - Controversy over strength of electric fields
3. System Generated EMP (SGEMP)
   - Disrupts/damages satellites

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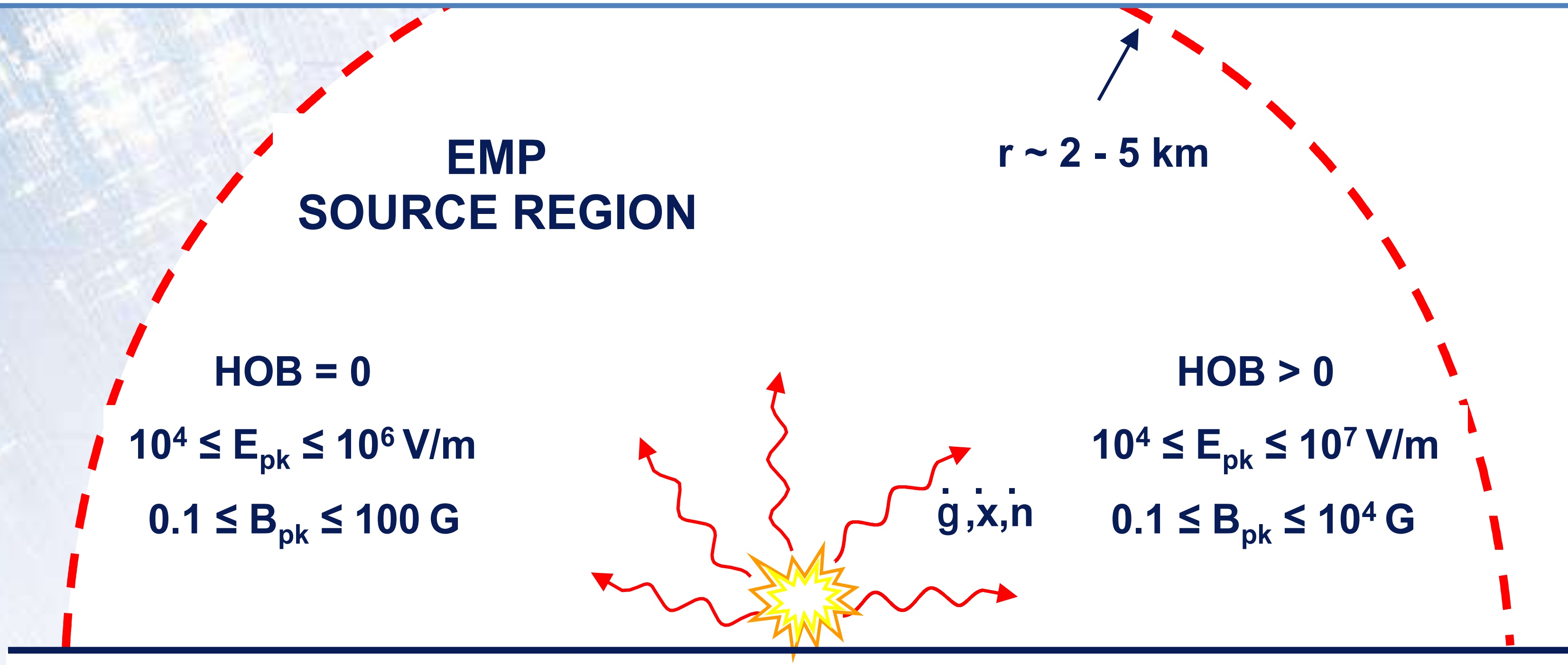
Background:
Source Region EMP (SREMP)

Source Region EMP Generation/Effects

The "source region" for a surface burst is typically 2 – 5 km if burst outside. It is the region where the initial radiation output (gamma, x-rays, neutrons) produces electron currents and air conductivity -- the sources for the SREMP

However, SREMP can disrupt systems over 100 miles away



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Source Region EMP – Why worry?

- 1945: Enrico Fermi predicted Source Region EMP with the first nuclear detonation at ground level (Trinity Test)
  - Even with shielding, some test equipment failed and records were lost
- During 1950s/60s surface burst tests, equipment/cables were damaged by SREMP in over 100 cases at the Nevada Test Site
  - Cables & connected equipment were damaged in almost every test
  - Circuit breakers tripped at Mercury (30 miles away) — needed reset
- In a 1953 test, a cable bundle was damaged at the Control Point (13 miles away) -- wires were melted
- A fire was started during SREMP testing of President's comms
- Electronics can be upset/damaged over 100 miles from burst
- SREMP can cause long-term regional power outages
- SREMP can damage electronics in deeply buried structures

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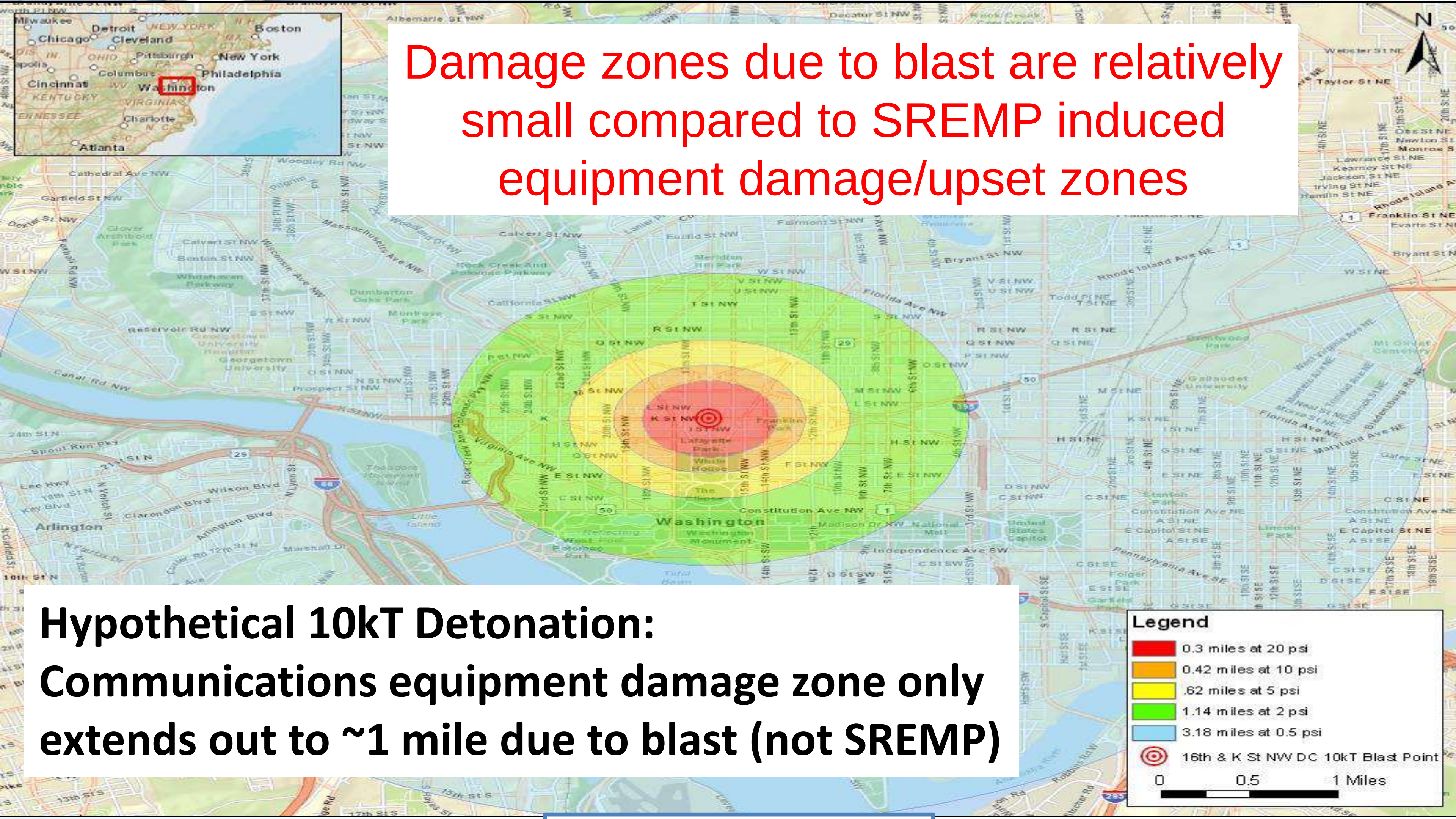
Calculated SREMP Line Coupling Damage/Upset for Various Yields

Yield (kT)	1.00	10.00	100.00	1000.00	3.00
	<------------	range to effect in km			------------->
Buried Telecomm Cable Damage	13.00	21.00	34.91	44.16	16.34
Buried Telecomm Cable Upset	18.00	26.00	39.98	49.19	21.45
Radial Overhead HV Powerline Damage	35.00	65.00	110.05	134.16	47.03
Radial Overhead HV Powerline Upset	46.00	85.00	143.00	174.00	61.66
0.5 km Offset Overhead HV Powerline Damage	0.30	23.00	33.00	44.00	2.38
0.5 km Offset Overhead HV Powerline Upset	0.30	43.00	66.00	84.00	3.21
1.0 km Offset Overhead HV Powerline Damage	0.10	10.00	20.00	31.00	0.90
1.0 km Offset Overhead HV Powerline Upset	0.10	30.00	53.00	71.00	1.52
25' Ethernet Cable Damage	6.18	10.31	11.44	12.18	7.89
25' Ethernet Cable Upset	18.75	36.43	41.55	44.83	25.75
100' Ethernet Cable Damage	11.34	21.04	23.76	26.40	15.23
100' Ethernet Cable Upset	41.11	77.42	86.88	95.84	55.60

10kT Peak Overpressure
In pounds per square inch (PSI)



Damage zones due to blast are relatively small compared to SREMP induced equipment damage/upset zones

Hypothetical 10kT Detonation:
Communications equipment damage zone only extends out to ~1 mile due to blast (not SREMP)

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10kT Source Region EMP (SREMP) Model
100’ Ethernet Cable Upset/Damage

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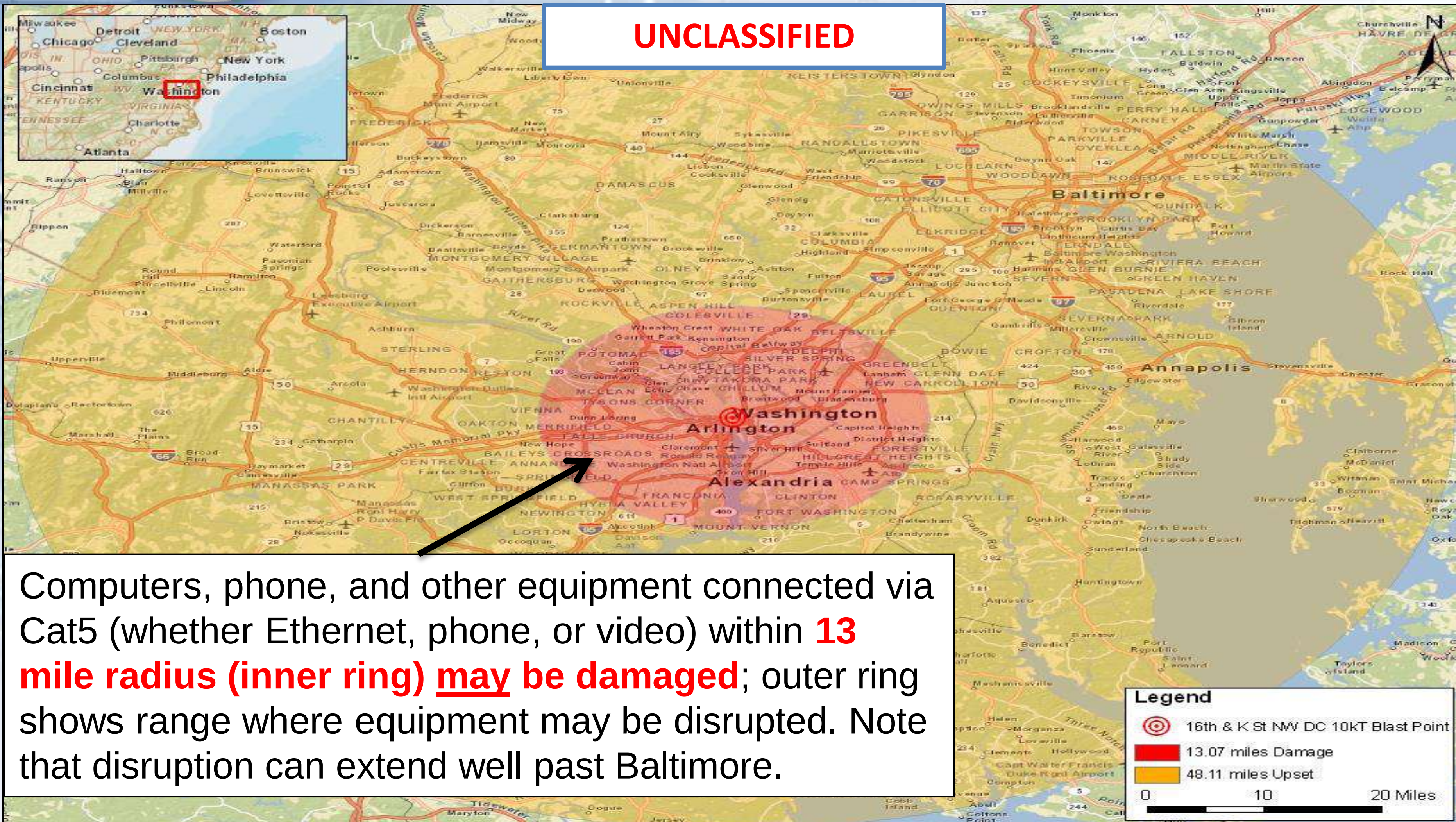

Computers, phone, and other equipment connected via Cat5 (whether Ethernet, phone, or video) within **13 mile radius (inner ring) <u>may</u> be damaged**; outer ring shows range where equipment may be disrupted. Note that disruption can extend well past Baltimore.

10kT SREMP Simulation – Cordless Phone Damage

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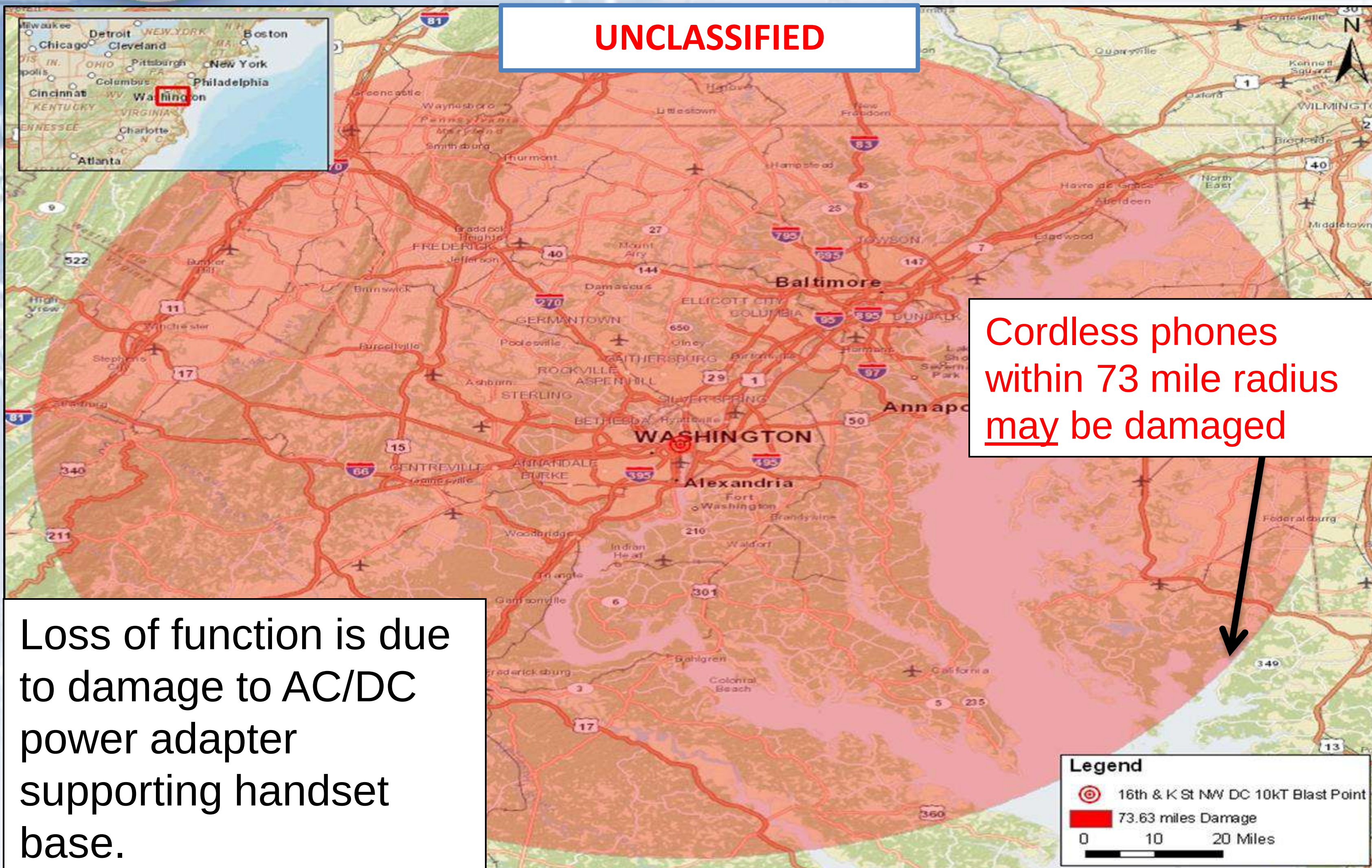

Cordless phones within 73 mile radius <u>may</u> be damaged

Loss of function is due to damage to AC/DC power adapter supporting handset base.

10kT SREMP Simulation – Potential FM Radio Transmission Upset/Damage

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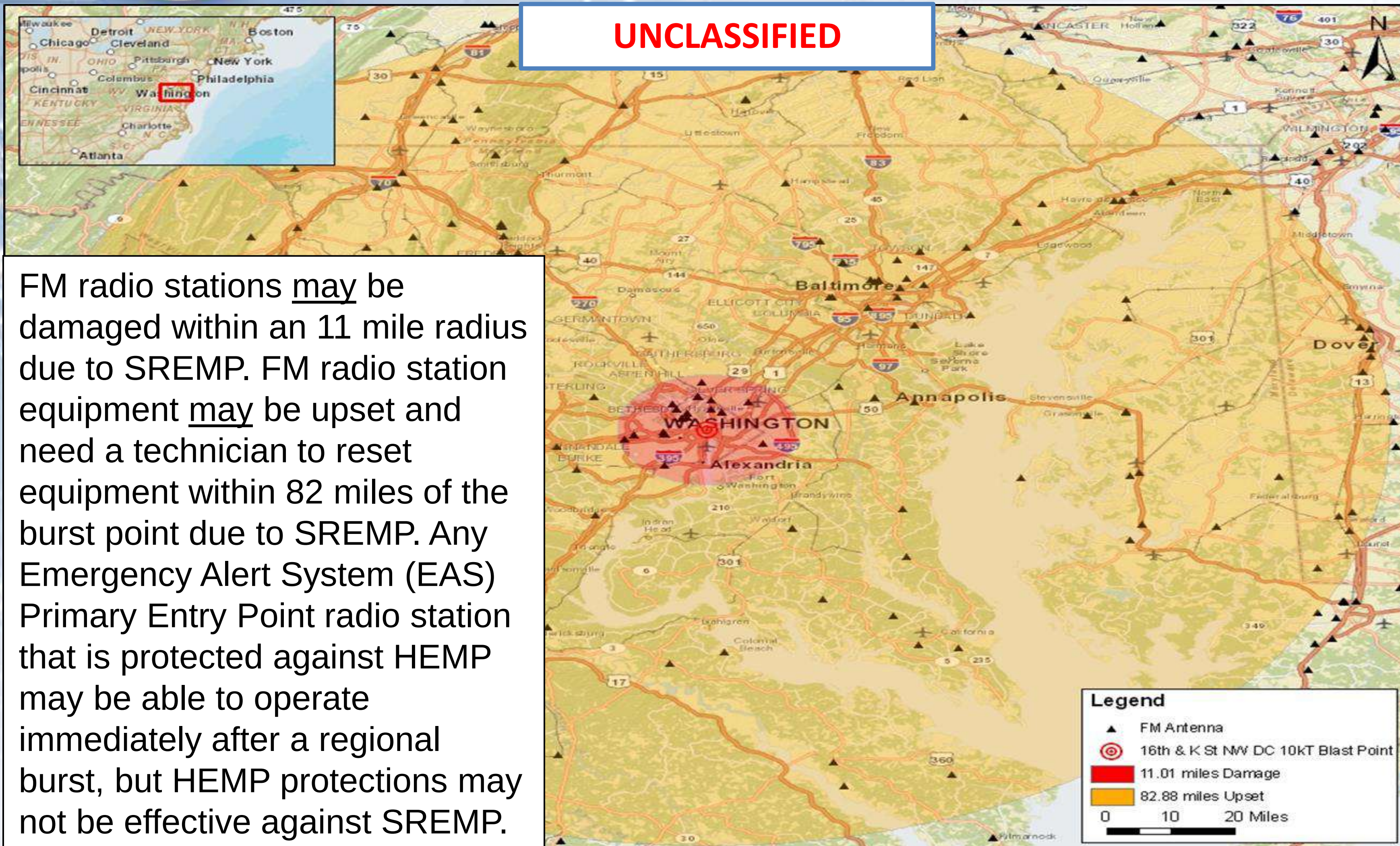
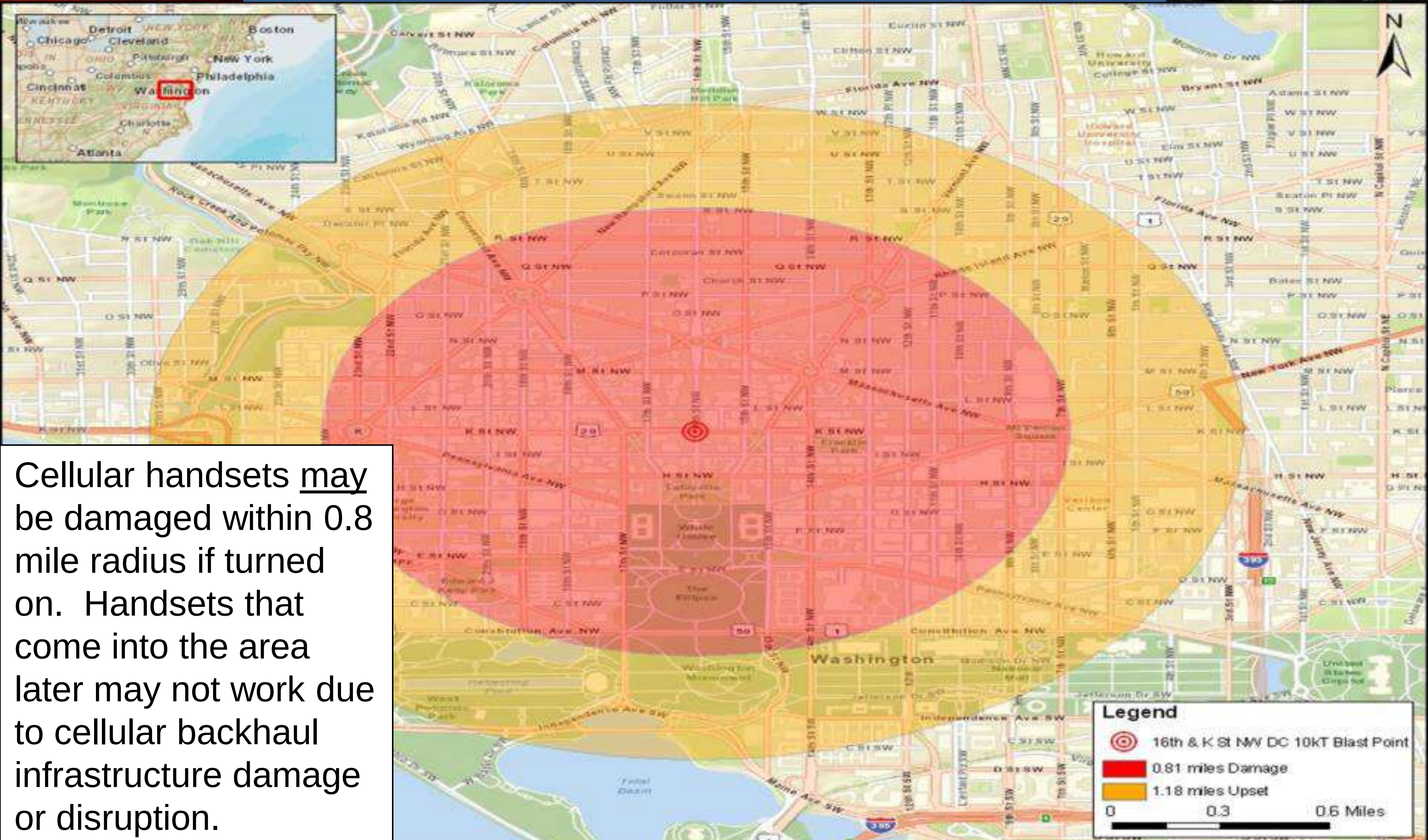


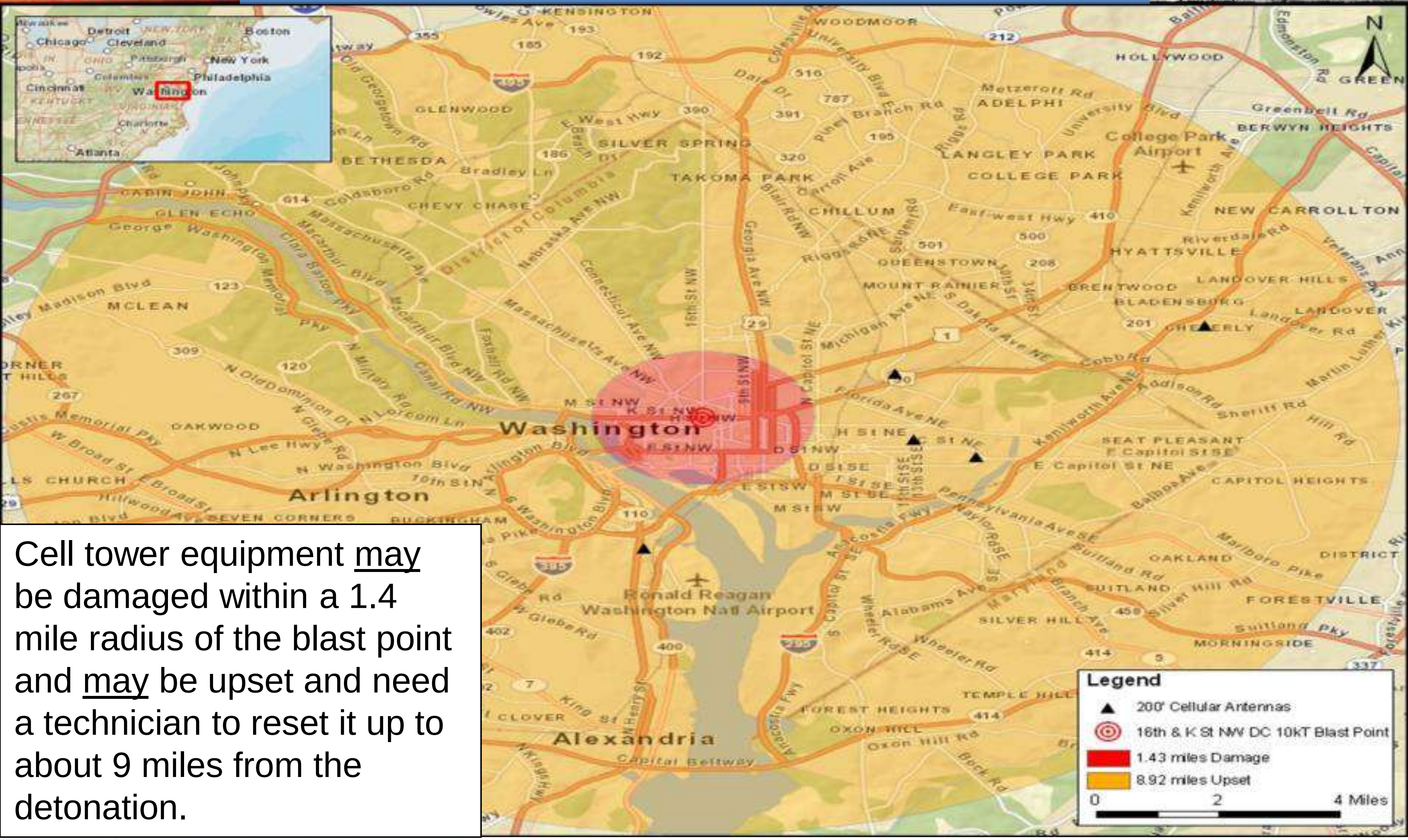
FM radio stations may be damaged within an 11 mile radius due to SREMP. FM radio station equipment may be upset and need a technician to reset equipment within 82 miles of the burst point due to SREMP. Any Emergency Alert System (EAS) Primary Entry Point radio station that is protected against HEMP may be able to operate immediately after a regional burst, but HEMP protections may not be effective against SREMP.

10kT SREMP Simulation – Cellular Handset Damage/Upset



Cellular handsets <u>may</u> be damaged within 0.8 mile radius if turned on. Handsets that come into the area later may not work due to cellular backhaul infrastructure damage or disruption.

10kT SREMP Simulation – 200' Cellular Tower Shield



Cell tower equipment <u>may</u> be damaged within a 1.4 mile radius of the blast point and <u>may</u> be upset and need a technician to reset it up to about 9 miles from the detonation.

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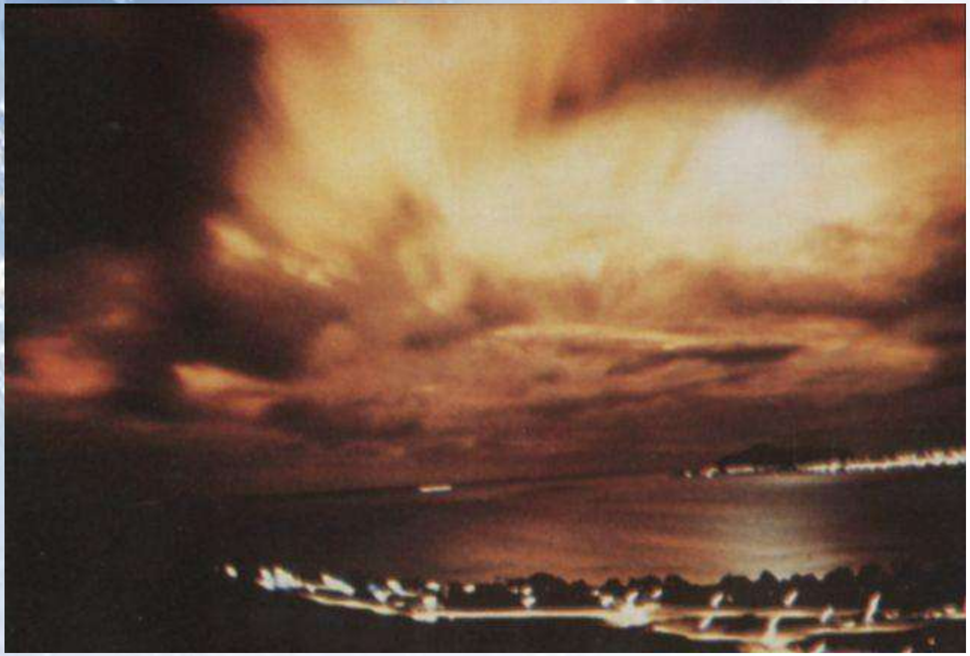
SREMP consequences for infrastructures and communications

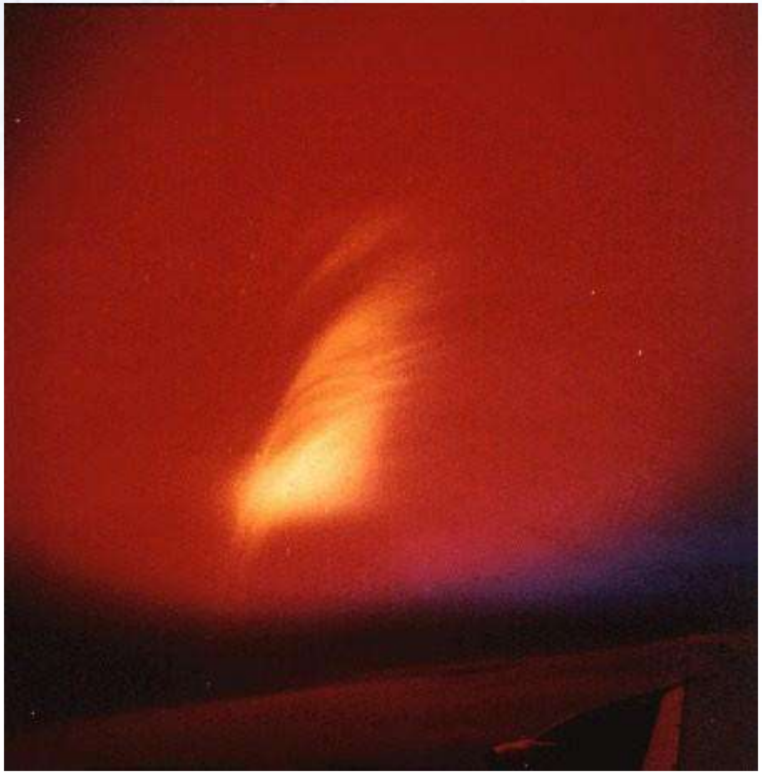
- Widespread, extended regional loss of power & communications
  - Catastrophic transformer failures at plants, substations, etc.
  - Power controls, relays, generators, computers are disrupted
  - Equipment connected to power or metallic data cables disrupted
- Consequences:
  - Immediate power outages in city/region complicates response
  - Loss of heating, air conditioning, lighting
    - Winter is worse case due to: (1) pipes bursting and (2) fires
  - Public may panic due to food/water/essential service outages
  - Telecommunications failures widespread after a few hours
  - If near nuclear power plant, could risk Fukushima-like issues
  - Restoration/response hindered greatly by nuclear fallout/fires

High Altitude EMP (HEMP) Risks

History of High Altitude EMP in USA



The July 1962 —Starfish Prime high altitude nuclear burst as seen through heavy cloud cover from Honolulu about 900 miles away. Aurora effects were observed for as long as 7 to 14 minutes in some areas.



The Starfish Prime air-glow aurora as seen at three minutes from a surveillance aircraft

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History of HEMP – USA

1962: U.S. "Starfish Prime" High Altitude EMP (HEMP) Test

- At midnight (9 July) over Johnston Island, a 1.4 MT device was detonated at 400 km (~ 250 miles) altitude ; a ~ 14 kV/m EMP resulted at Johnston Island
- At 100 nanoseconds, Hawaii experienced a 5.6 kV/m EMP
  - Blew fuses supporting ~ 300 street lights in Oahu (~ 900 miles away)
  - Damaged a microwave link that then shut down telephone service between Kauai to the other Hawaiian islands
  - Other: some car ignition systems fused and burglar alarms went off
- Artificial radiation belt of trapped electrons damaged many satellites
  - Solar panels degraded; most satellites failed (within days to 6 months)
- HF radio was disrupted for minutes to hours in the region; HF TRX's damaged

A similar burst over the central USA today would likely shut down commercial power and communications in large regions for months or longer

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High Altitude EMP (HEMP)
Most significant EMP; has 3 components

1. **E1** is the fast (less than microsecond) and powerful pulse that can destroy computers and communications equipment and disrupt power grids
2. **E2** occurs from 1 microsecond out to 1 second and is generated by gammas produced by weapon neutrons and is less powerful than the E1 pulse
   - The main risk with the E2 component is that it immediately follows the E1 component, which may have damaged the lightning protection devices that would normally also have protected against E2
3. **E3** is a slow pulse that arrives after 1 second and can last several minutes
   - E3 can penetrate the ground and water; similar to solar storm EMP
   - E3A (Blast) occurs in 1 – 10 seconds; E3B (Heave) in 10 – 300 seconds
   - E3 can produce damaging surge currents in long electrical conductors like power lines or undersea cables

See Meta-R-319 through Meta-R-324 for more information on the various types of EMP

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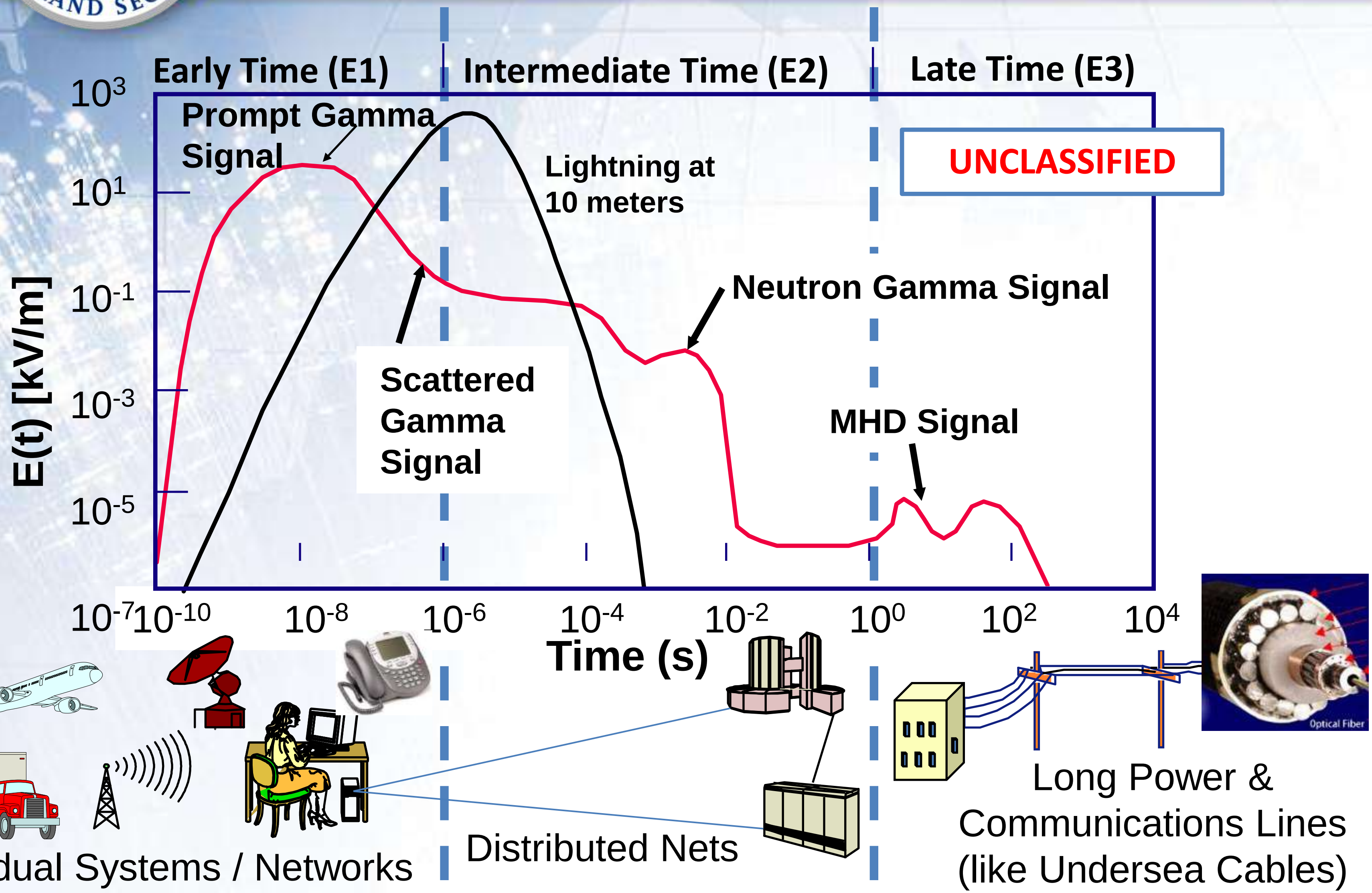
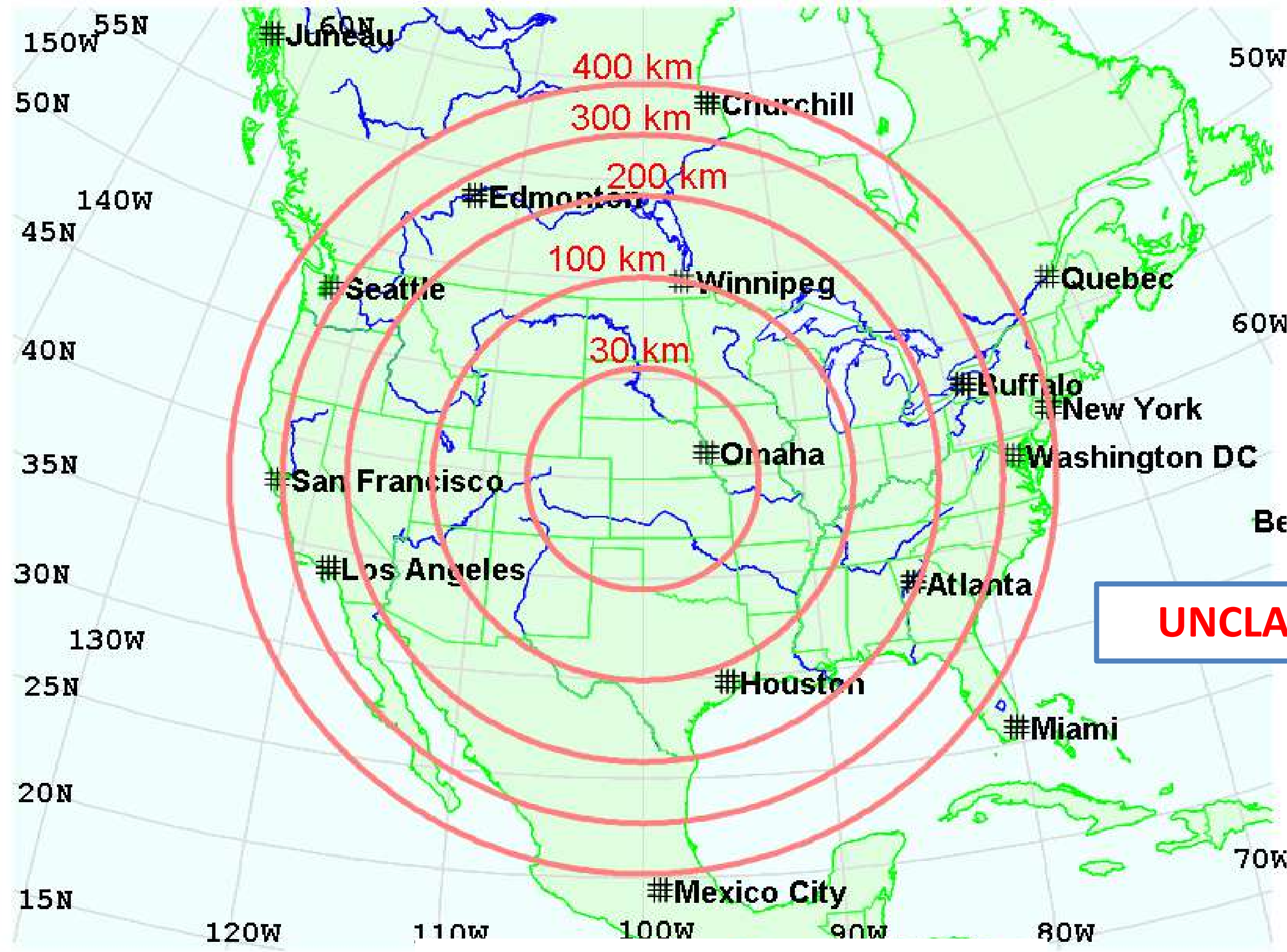
HEMP – E1, E2, & E3 described



HEMP E1 Area Coverage

Exposed region for various burst heights (HOB):



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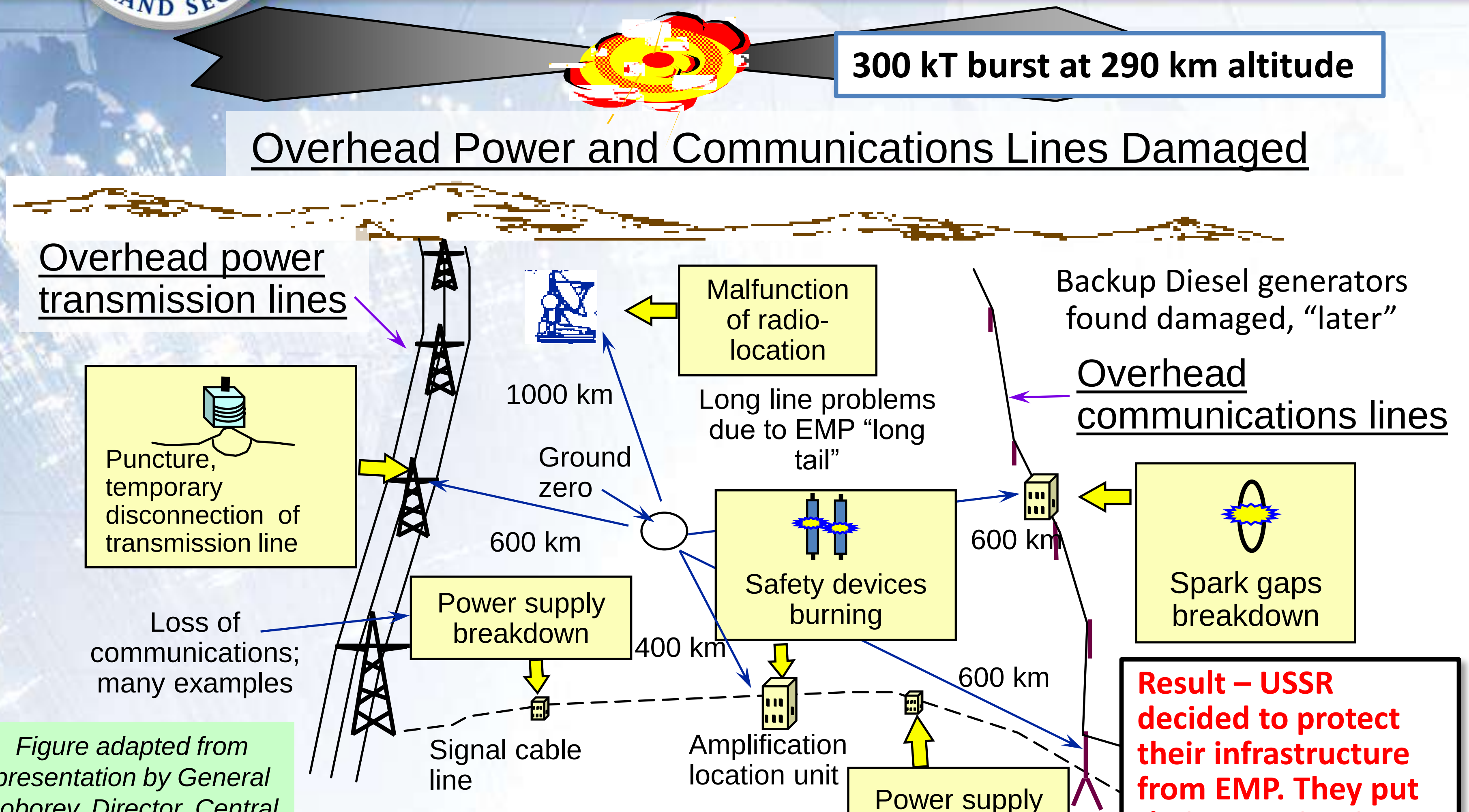
EMP – Lessons from Soviet History
Oct 1962 K-3 HEMP Test Results



Result – USSR decided to protect their infrastructure from EMP. They put their top scientists on this EMP project.

Figure adapted from presentation by General Loborev, Director, Central Institute of Physics and Technology, June 1994

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EMP – Lessons from Soviet History

- **1962: Soviet K-3 HEMP Test (U.S. designation: Test #184)**
  - **22 October 1962 (~ 6 AM): During the Cuban missile crisis, the Soviets detonated a 300 kT device at 290 km HOB over Kazakhstan's Sary Shagan ABM Test Range**
  - **Soviets experienced outages on ~ 500 kilometer long telephone line**
    - **Line was protected by gas-filled surge arresters (R-350) and fuses (SN-1)**
    - **Arresters fired and fuses were blown out at <u>all</u> repeater points due to EMP**
    - **Based on later testing, R-350 arresters were shown to fire at 350 ± 40 V**
    - **Up to 7.5 kV/m peak E1 (< 1 µs) field strengths were estimated :**
      - **E1 peak induced voltage on 80 km subline 1 was > 20 kV [R-350 fired]**
      - **E1 peak induced current was approximately 65 A [not blow fuse]**
    - **E3 amplitude did not exceed 5 V/km (for 80 km segment, total V = 400V)**
      - **E3 would have caused the R-350 to fire, but E1 prevails for damage**
      - **E3 current of several seconds of 4A easily blows the fuses (fail at ~1 A)**

Q: Have you fixed the problems? A: … All trunk lines are now underground, which was a Ministry of Communications initiative to protect civilian communications.

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Prime Sources: Greetsai, Vasily N., et al. "Response of Long Lines to Nuclear High-Altitude Electromagnetic Pulse (HEMP)" IEEE Transactions on Electromagnetic Compatibility, Vol. 40, No. 4, November, 1998 ; and http://nuclearweaponarchive.org/News/Loborev.txt [see notes page for additional info]

EMP - Lessons from Soviet History (continued)

- **1962: Soviet K-3 HEMP Test (U.S. designation: Test #184) / cont.**
  - **Q: What were the effects on electricity generation …?**
  - **A: Generators (fixed diesel plants) & substations were damaged by E1**
  - **Effects on power plant and power cables (& buried telecomm cables)**
    - **E3 EMP penetrated 0.9 meters into the ground, overloading a shallow buried lead and steel tape-protected 1,000-km long power cable; firing circuit breakers and setting the Karaganda power plant on fire …**
    - **"The 1,000 km long Aqmola-Almaty power line was a lead-shielded cable … it succumbed completely to the low frequency EMP at 10-90 seconds after the test, since the low frequencies penetrated through 90 cm of earth, inducing an almost direct current in the cable, that overheated and set the power supply on fire at Karaganda, destroying it. … This overheated the transformers, which are vulnerable to short-circuit by DC."**
    - **Many failures of buried long line telecom & power systems were noted [Radasky]**

Prime Sources: Greetsai, Vasily N., et al. "Response of Long Lines to Nuclear High-Altitude Electromagnetic Pulse (HEMP)" IEEE Transactions on Electromagnetic Compatibility, Vol. 40, No. 4, November, 1998; and http://nuclearweaponarchive.org/News/Loborev.txt

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What can EMP do?

Testimony of the Chairman of the EMP Commission: "Depending on the specific characteristics of the EMP attacks, unprecedented cascading failures of major infrastructures could result. In that event, a regional or national recovery would be long and difficult, and would seriously degrade the safety and overall viability of our Nation. … The recovery of any one of the key national infrastructures is dependent upon the recovery of others. The longer the outage, the more problematic and uncertain the recovery will be. It is possible for the functional outages to become mutually reinforcing until at some point the degradation of infrastructure could have irreversible effects on the country's ability to support its population." www.empcommission.org/docs/GRAHAMtestimony10JULY2008.pdf

EMP Commission finding: "The Congressional EMP Commission estimates that, given the nation's current unpreparedness, **within one year of an EMP attack, two-thirds of the U.S. population — 200 million Americans — would probably perish from starvation, disease and societal collapse**." www.washingtontimes.com/news/2012/dec/19/north-korea-emp-attack-could-destroy-us-now/#ixzz2TEqorSvV

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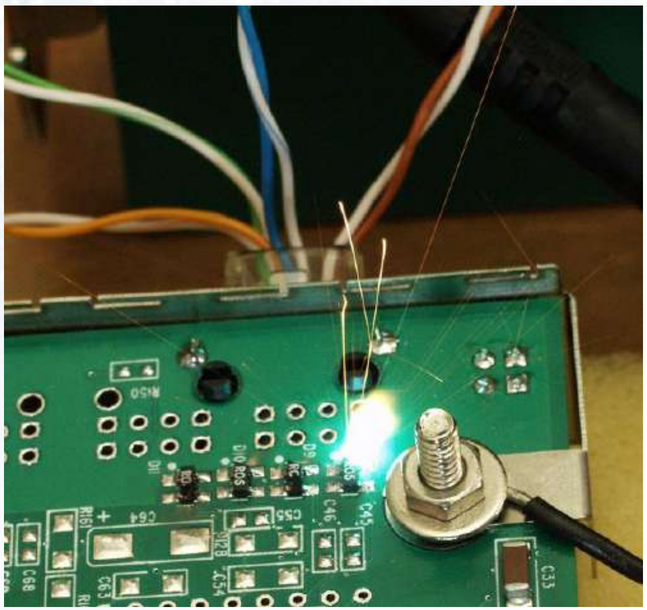
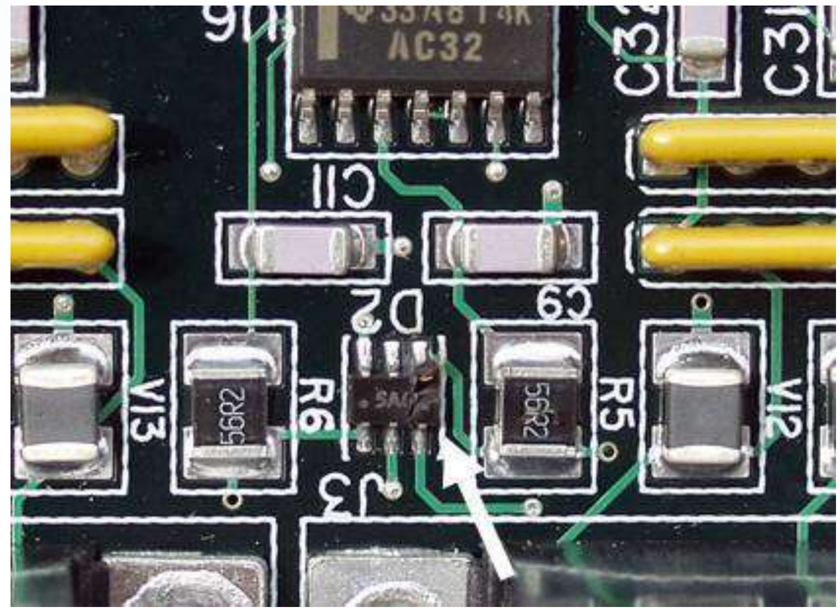
High-Altitude Electromagnetic Pulse Effects on Electronics

- **There are no similar natural effects that routinely would be as strong – but HEMP is somewhat like:**
  - **Electrostatic Discharge (ESD) fields have some similarities to early part of HEMP – E1.**
  - **Solar magnetic storms are similar to late part of HEMP – E3.**
- **HEMP is of concern for electronic equipment – upset or damage.**



Network interface "blowing up" – here from a SCADA unit

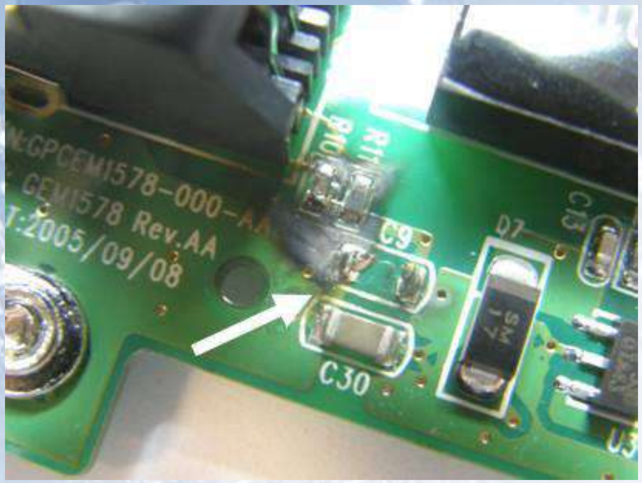


Damaged part from pulsing of a timing port in a SCADA unit

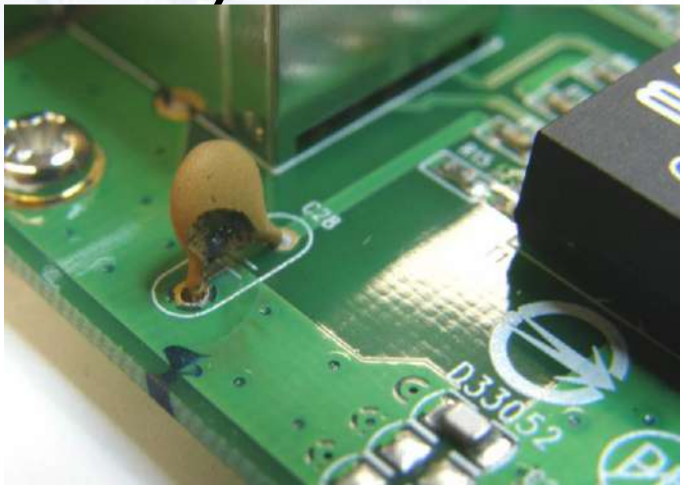
(SCADA = "supervisory control and data acquisition", electric power grid controls.)

More Damage Examples, NIC Cards

NIC = Network Interface Cards (Ethernet card for PCs)



In-line capacitor completely blown off a NIC.



A ceramic capacitor with a piece blown off; from a NIC.

The main IC of a NIC – with the lid scorched and deformed.

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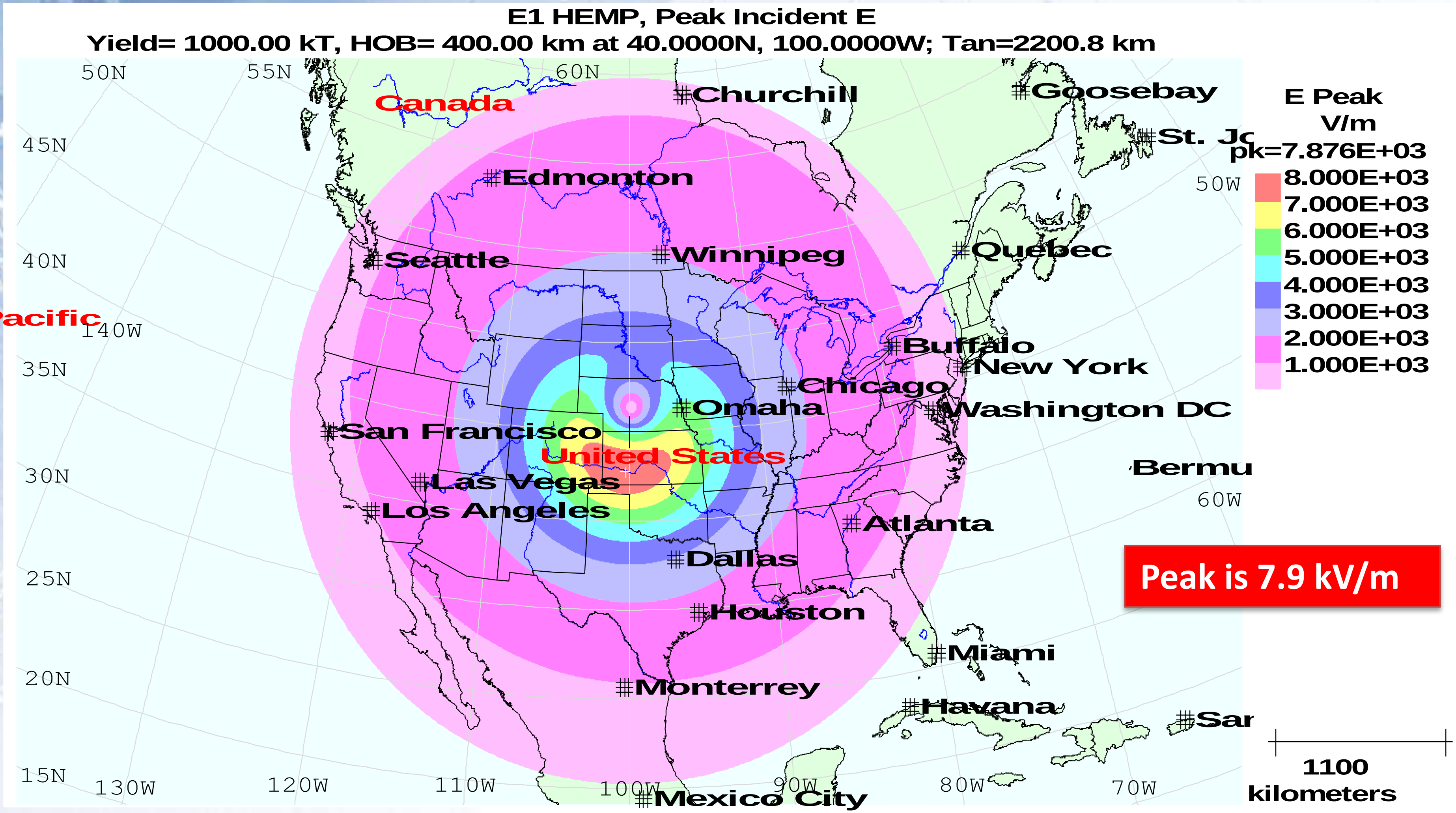
E1 HEMP peak voltage from 1 MT detonation over the USA



Peak is 7.9 kV/m

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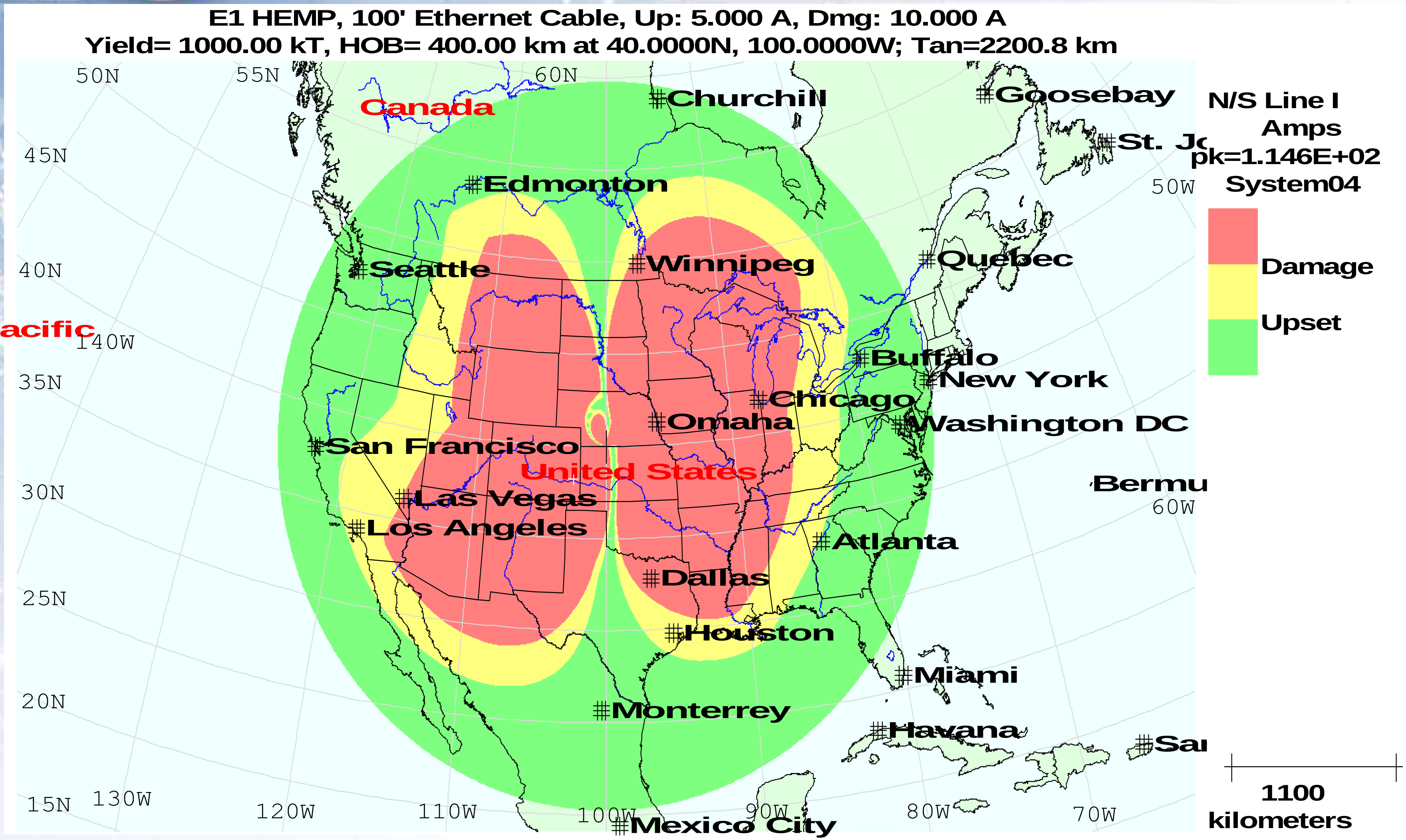
Impacts: E1 Potential Upset/Damage Areas for 100’ North/South Oriented Cat 5 Cables



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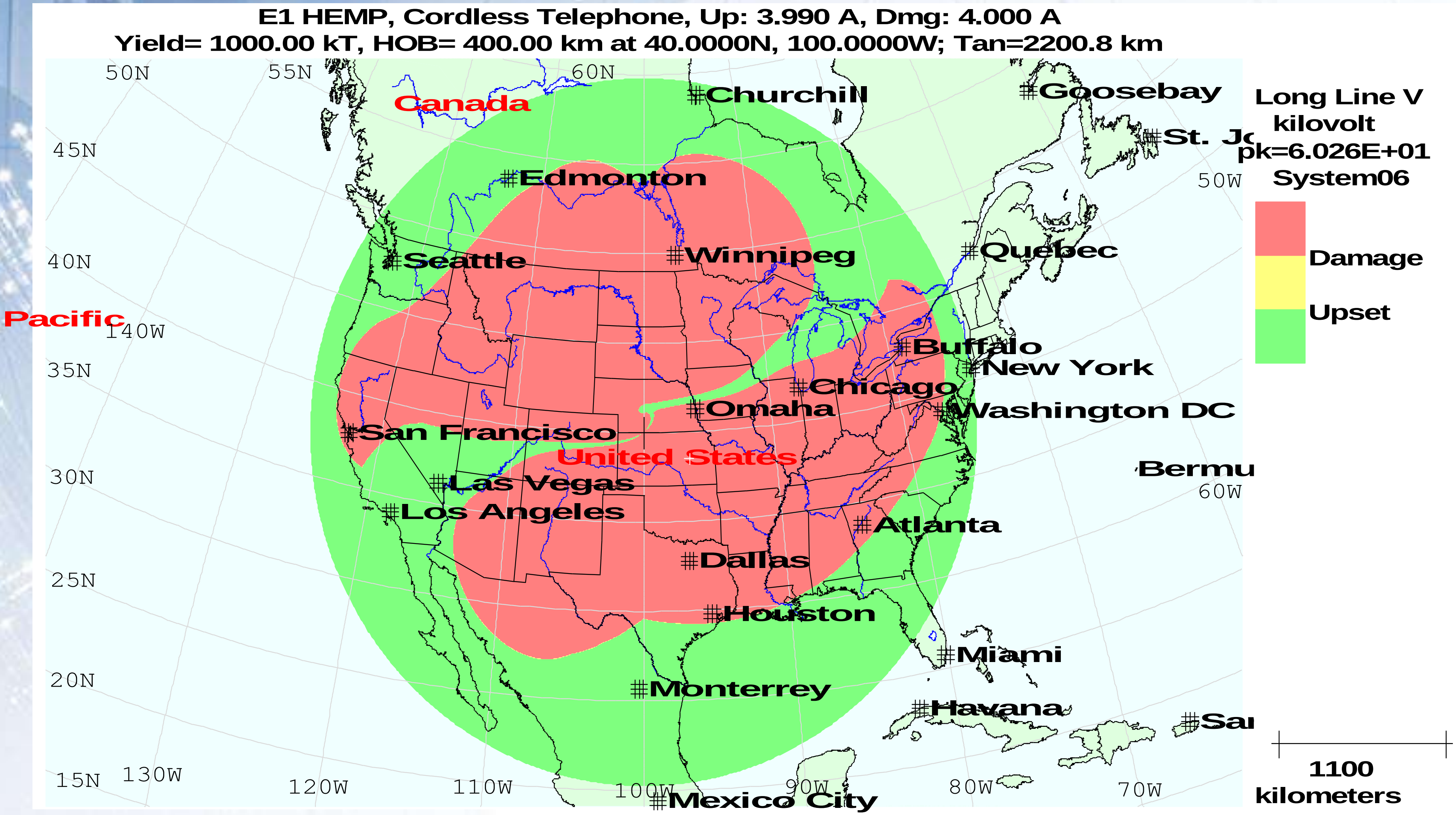
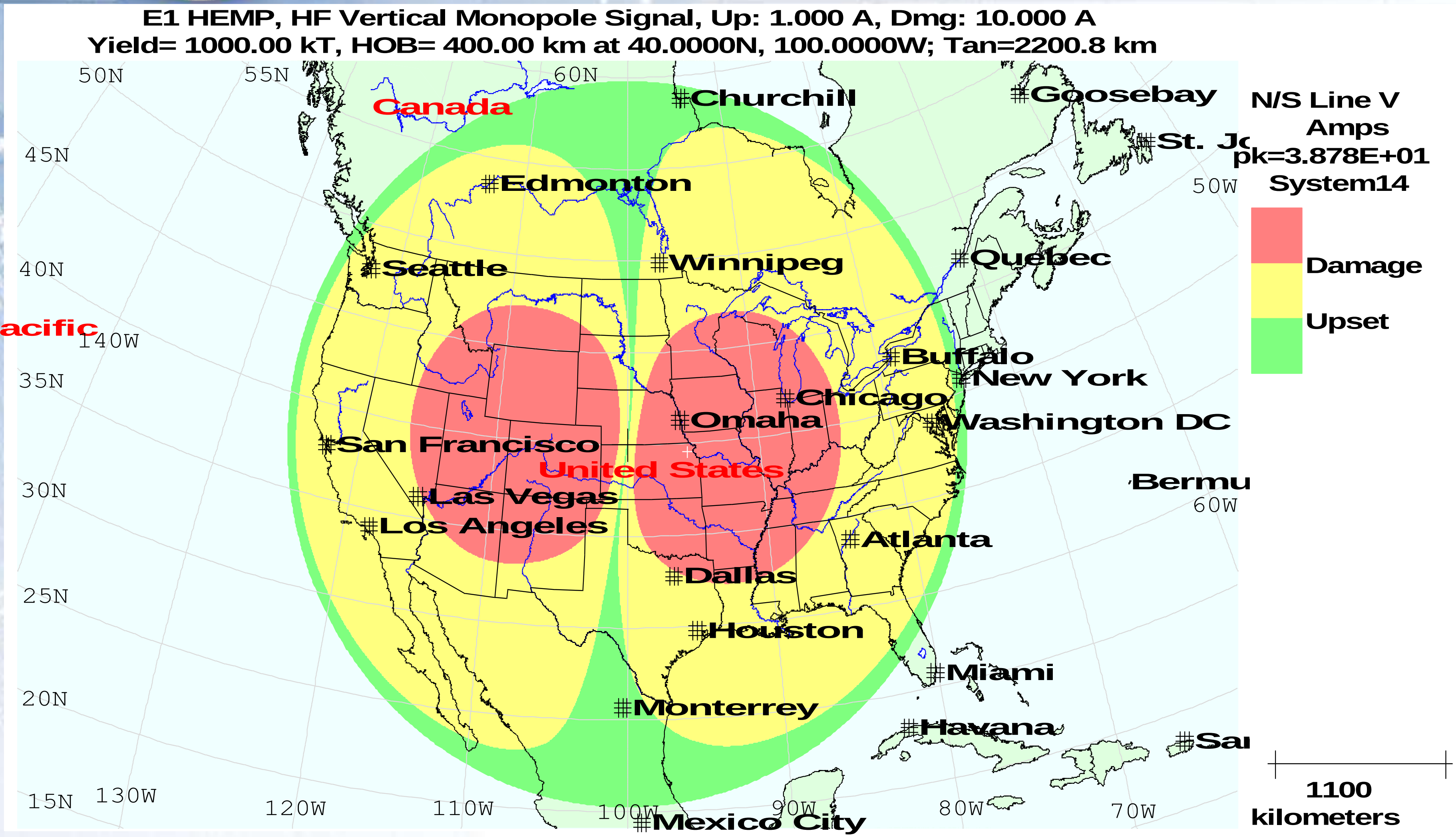
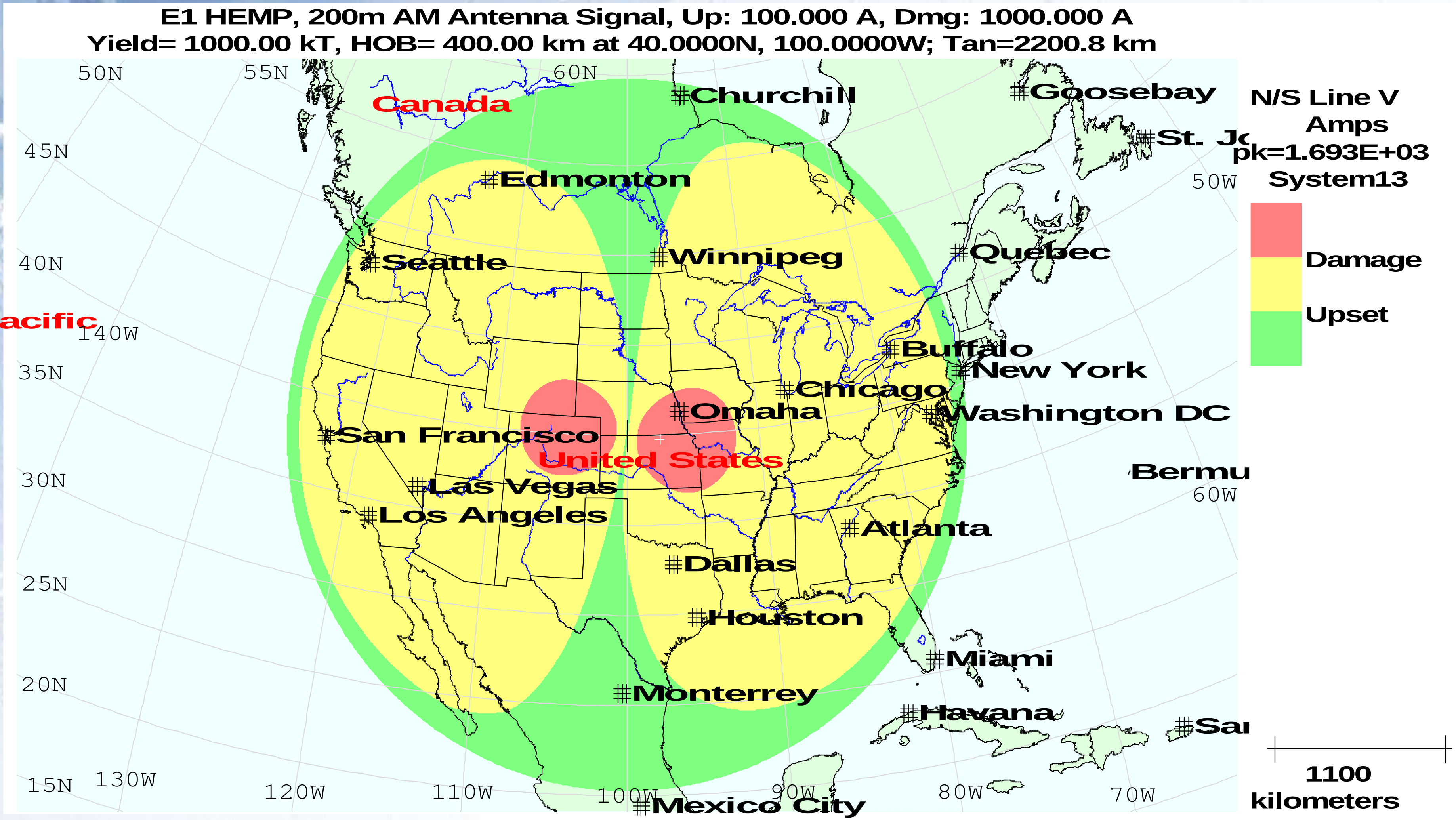
Impacts: E1 HEMP Potential Upset/Damage Areas for E/W Cordless Phone AC/DC Adapter



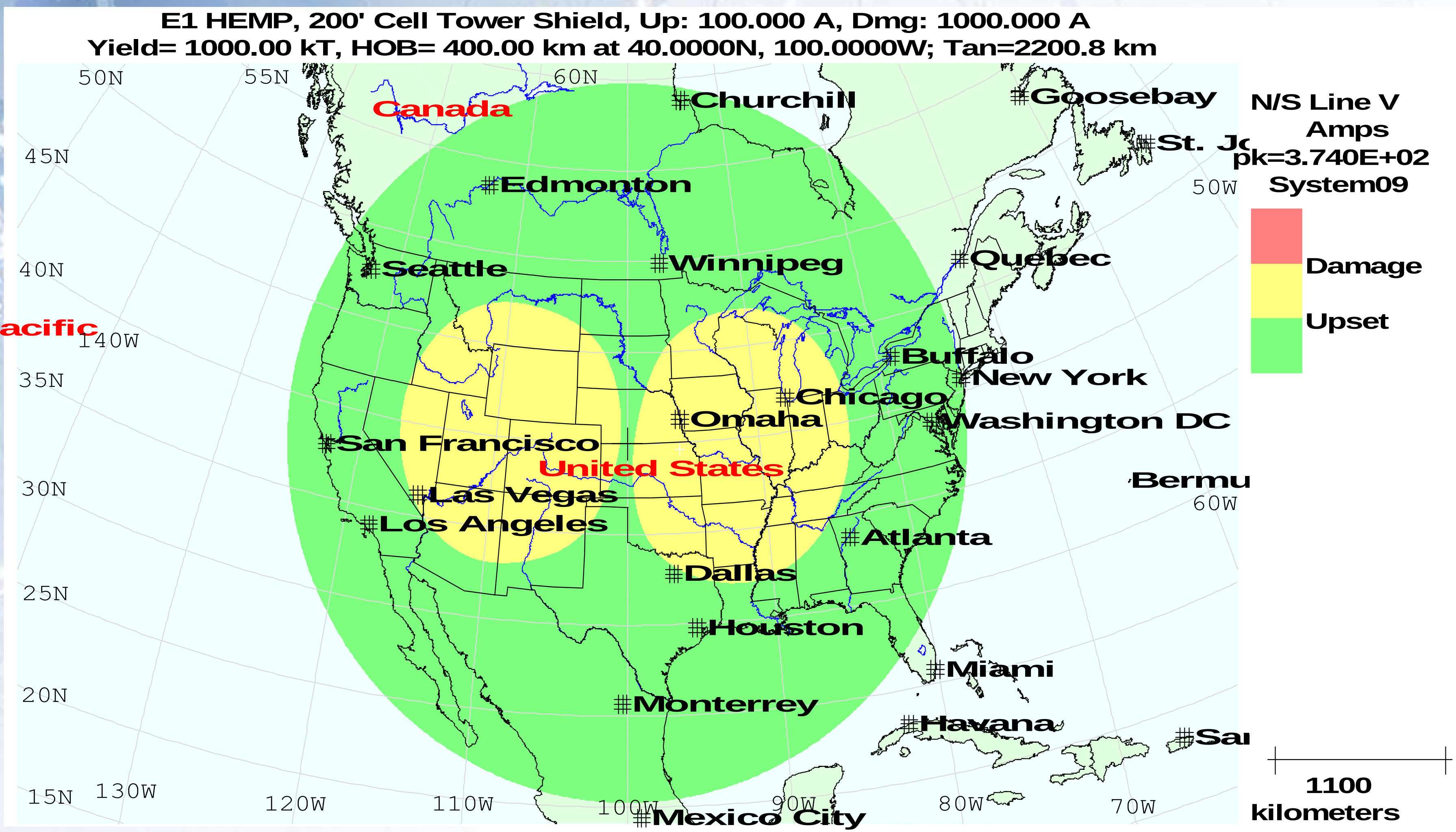
Impacts: E1 HEMP Potential Upset/Damage Areas for Vertical Monopole HF Antenna/Radio



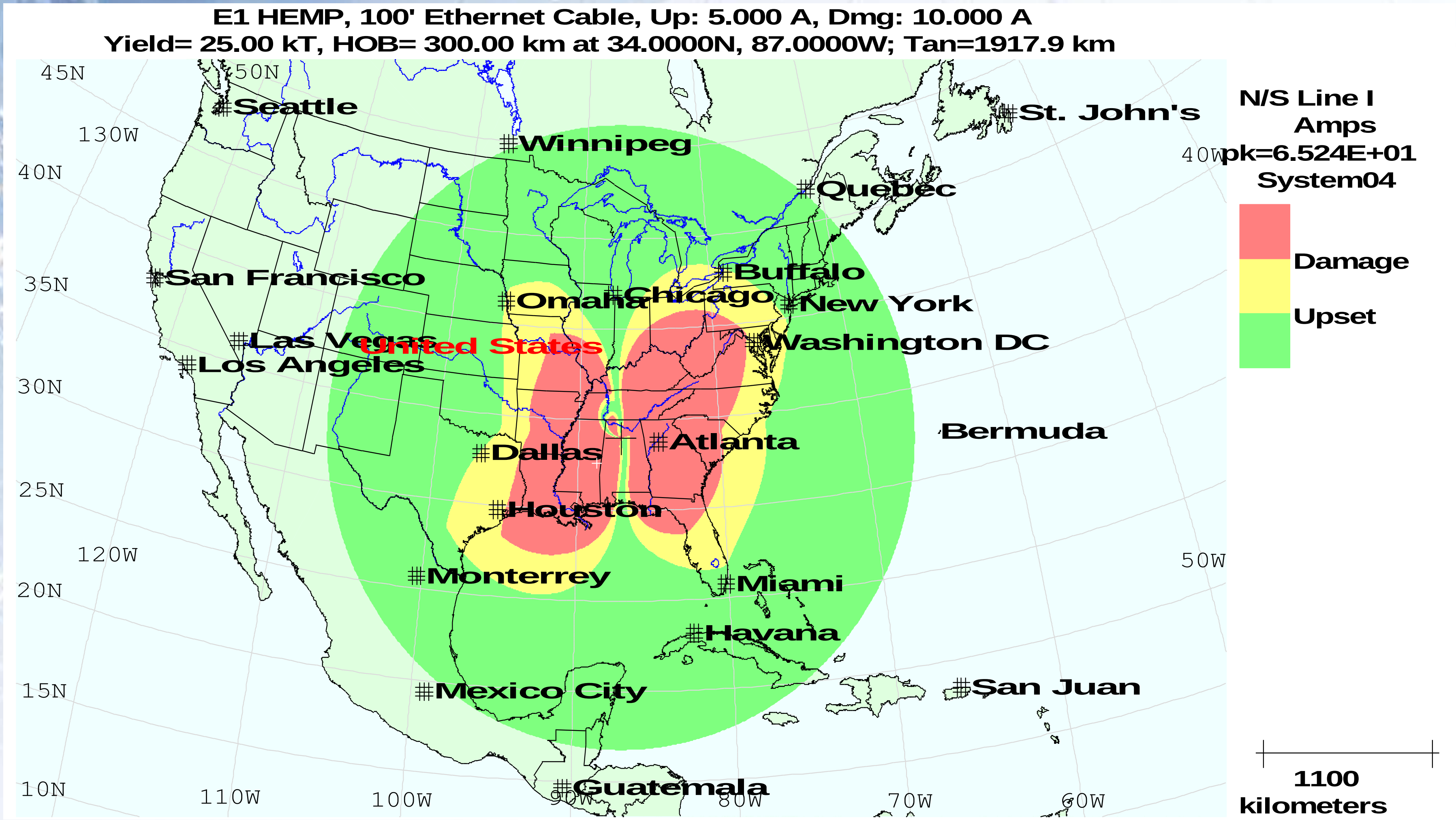
Impacts: E1 HEMP Potential Upset/Damage Areas for 200 meter tall AM Radio Tower Shield



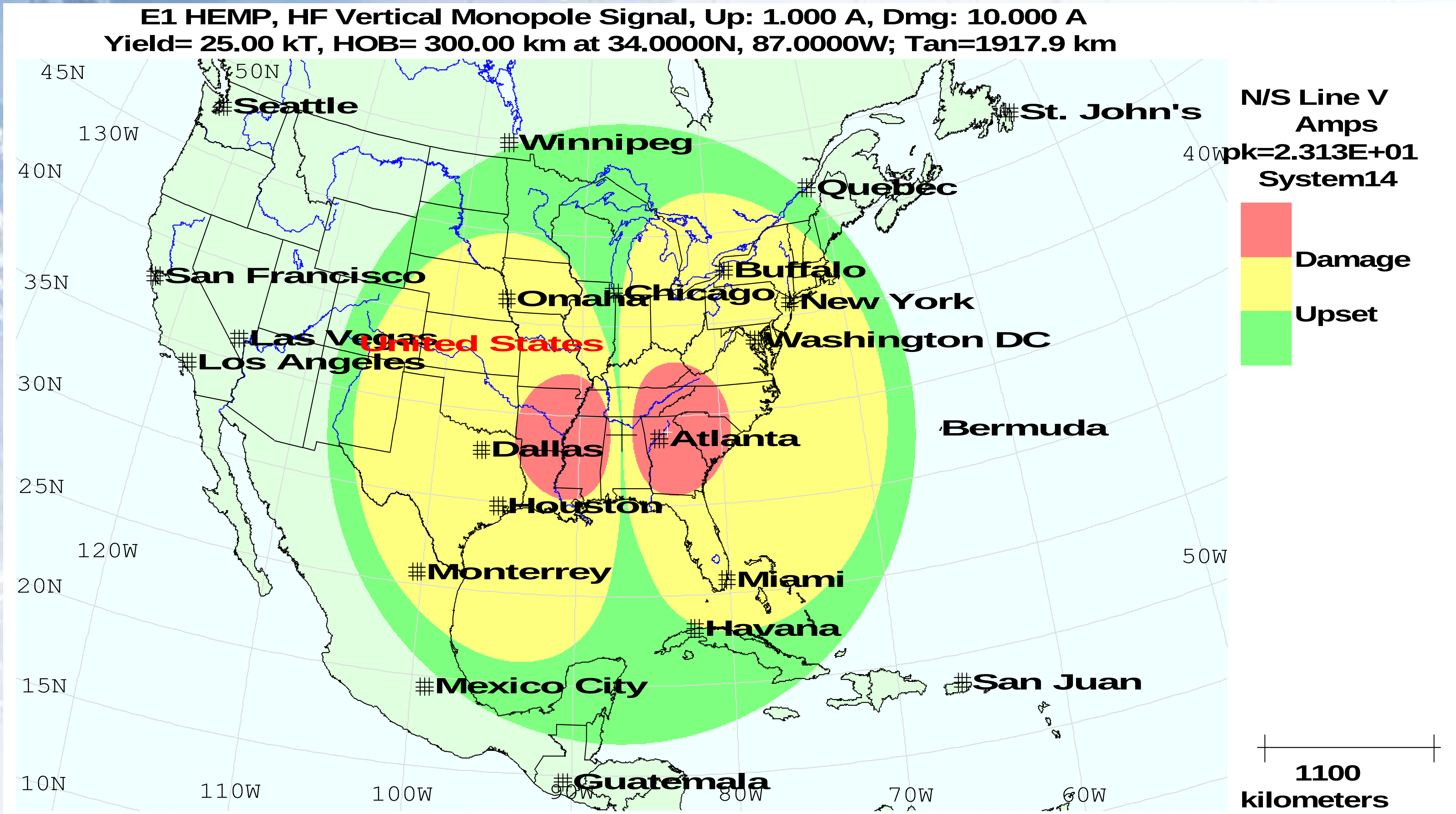
Impacts: E1 HEMP Potential Upset/Damage Areas for 200 foot Cell Tower Shield



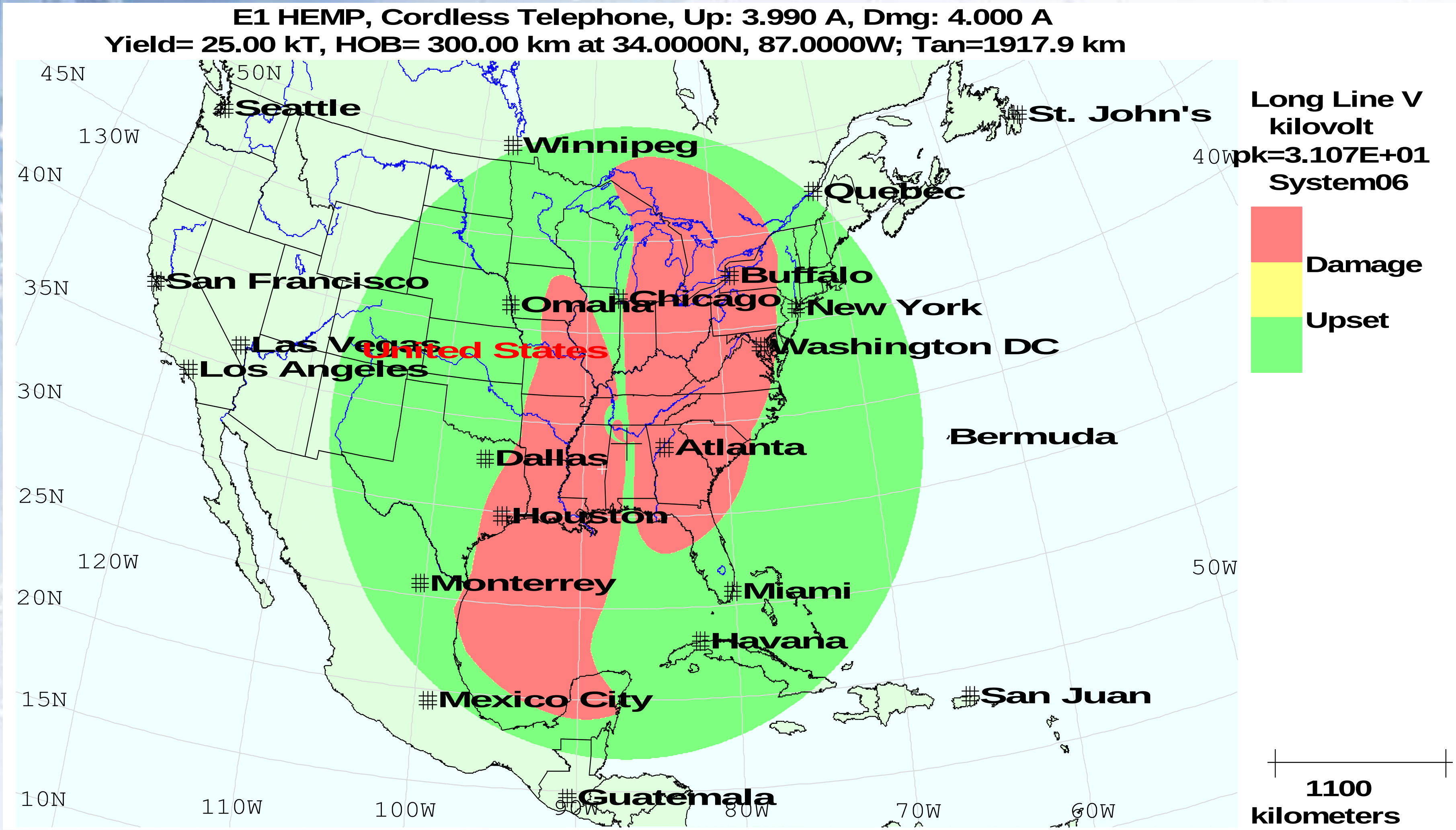
25 kT Gulf Launch: E1 HEMP Potential Upset/Damage Areas for 100' N/S Ethernet



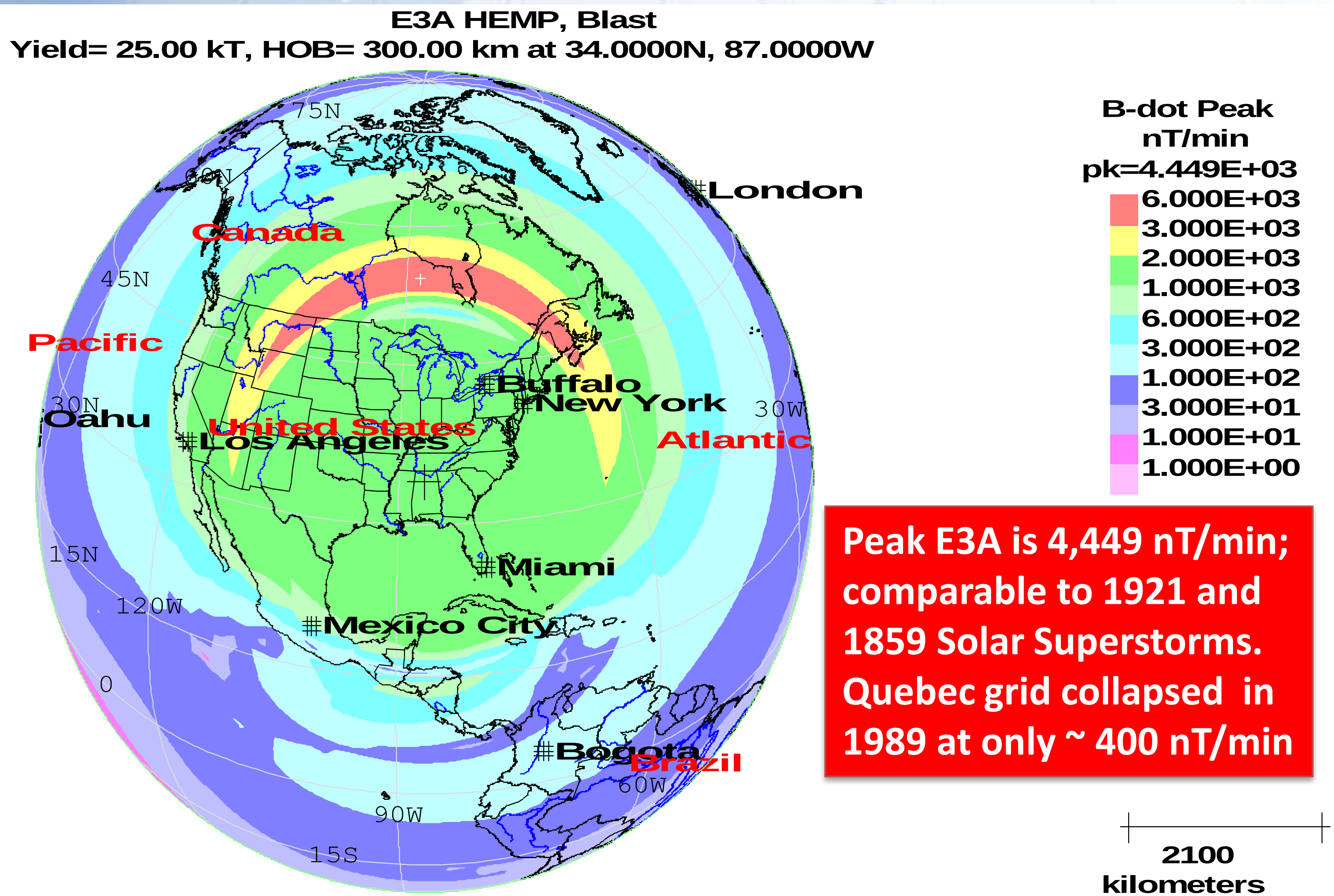
25 kT Gulf Launch: E1 Potential Upset/Damage Areas for HF Vertical Monopole Antenna/Radio



25 kT Gulf Launch: E1 Potential Upset/Damage Areas for Cordless Phone AC/DC Adapter

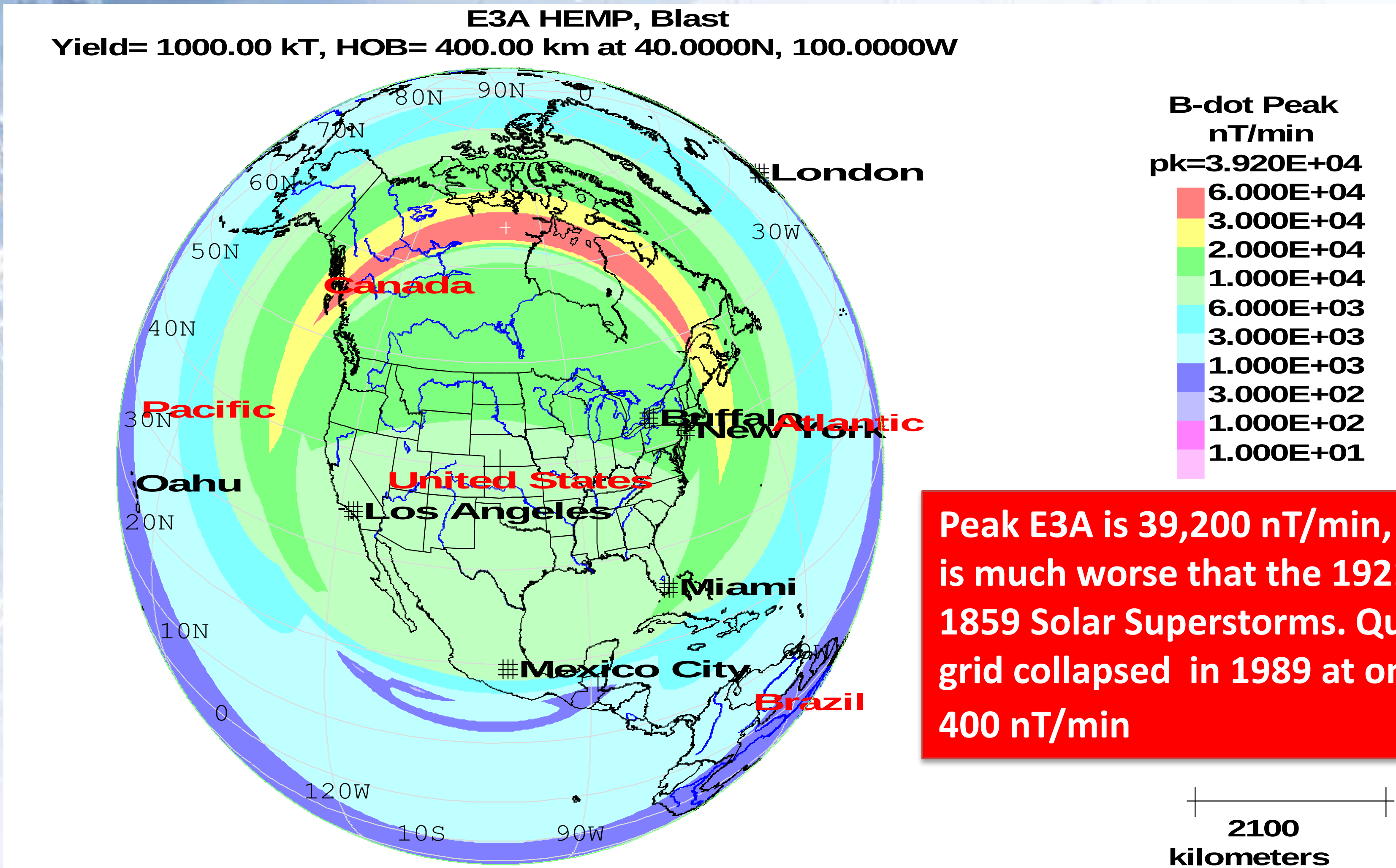


25 kT Gulf Launch: E3A HEMP Peak nT/min from 25 kT Detonation over Alabama



Peak E3A is 4,449 nT/min; comparable to 1921 and 1859 Solar Superstorms. Quebec grid collapsed in 1989 at only ~ 400 nT/min

1MT Burst over Central USA
E3A HEMP Peak nT/min

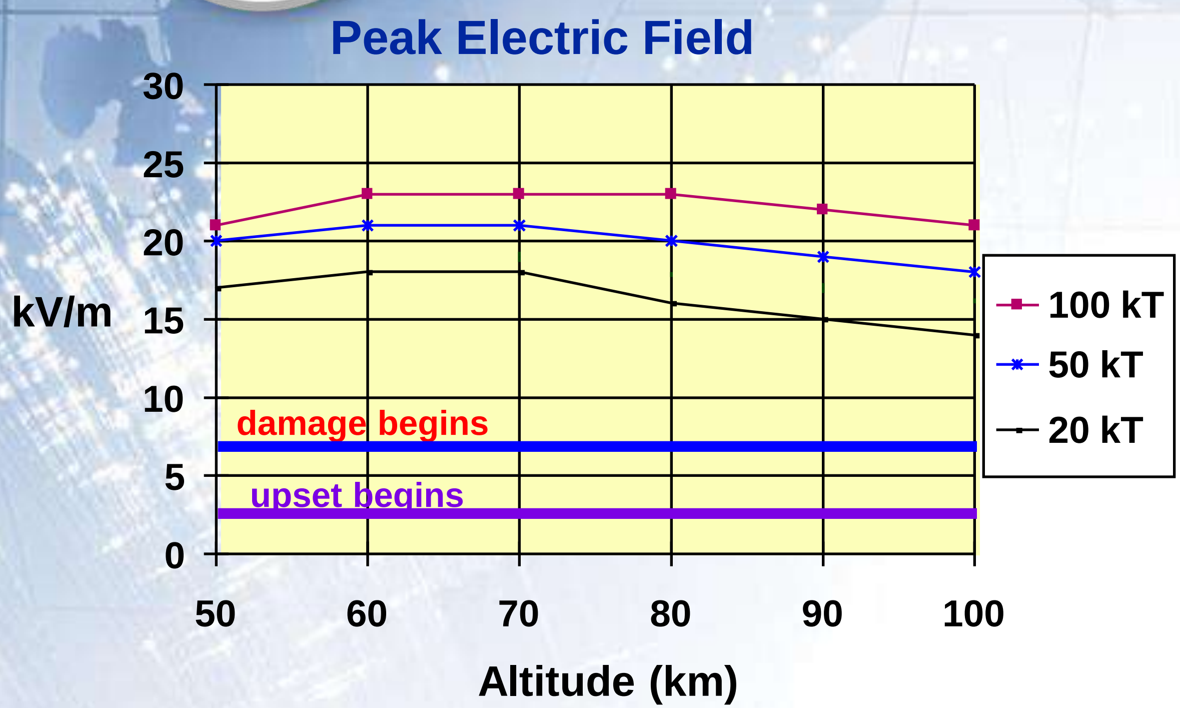


Peak E3A is 39,200 nT/min, which is much worse that the 1921 and 1859 Solar Superstorms. Quebec grid collapsed in 1989 at only ~ 400 nT/min

EMP Hardening Issues/Approaches

- **Need to develop guidance for protecting against all forms of EMP, to include: HEMP, Source Region EMP (SREMP), RF Weapons, Solar, etc.**
- **Determine if system requires Military Standard HEMP protection approach**
  - Is the system time-urgent under Department of Defense directives?
  - If so, the military HEMP hardening standard should be used (MIL-STD-188-125)
- **If MIL-STD not required, use standards or latest DHS guidelines**
  - International Telecommunication Union (ITU) standards (K.78, K.81)
  - International Electrotechnical Commission (IEC) standards (SC 77C's 61000 series)
  - DHS EMP Protection Guidelines for Equipment, Facilities, and Data Centers
- **Need massively scalable, cost-effective approaches:**
  - Use bolted together equipment shelters where possible (versus welded designs)
  - Develop/use low-cost automated, remote, test, verification, and monitoring units
  - Develop low-cost power isolation techniques to help handle SREMP risks
  - Develop and test methods of cost-effectively removing all metallic power and data cables in buildings, undersea cables, and to equipment and remote antennas

Hardening against HEMP



Hardening Techniques (MIL-STD-188-125)

- RF Shielding (Faraday shield)
- Aperture treatment
- Electrical penetration treatment
- Grounding

Cost to Harden using DoD approach (% of System Cost)
Assumes "forward fit" vice retrofit
if use MIL-STD 188-125

Tactical Systems	1-2%
Fixed Facilities	2-3%
Aircraft	5%
Cruise Missiles	5%
Strategic Missiles	5%

DHS EMP Protection Guidelines *

Electromagnetic Pulse (EMP) Protection Guidelines for Equipment, Facilities and Data Centers

Version 6.0

11 May 2015

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* Note: Guidelines are preliminary and subject to change

Four EMP Protection Levels (Preliminary)

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Level 1	Level 2	Level 3	Level 4
Use MIL-STD-188-125-1 and MIL-HDBK-423 HEMP shielding protection with brazed or welded EMP rooms to protect key equipment; HEMP surge protection devices (SPDs) throughout facilities or buildings outside of shielded areas. Use true on-line/double conversion UPS for further power protection. Use MIL-STD double-door entryways.	Protect all external power and data line entries. In addition, use EM shielded rooms around critical equipment (like computer servers and data storage units, phone PBXs, HVAC, and backup power units). Rooms can be non-welded, bolt-together designs; use EMP SPDs throughout facilities or buildings outside of shielded areas. Can use single-door entryways. Use true on-line/double conversion UPS for further power protection. Reference IEC SC 77C standards for design guidance and testing.	Protect power & data lines (as with Level 4) plus protect all external power entries; any analog phone lines and cables coming in from any external antennas (such as HF, VHF, or UHF antennas) with EMP filters; use true on-line/double conversion UPS for further power protection; use fiber optic data cables where possible, otherwise use shielded network cables; use EMP SPDs throughout facilities or buildings; no shielded rooms are required (but recommended)	Use EMP capable surge protector strips (< 1 nanosecond response time) on power cords for essential equipment; use EMP SPDs throughout facilities or buildings; use EMP spark/fire suppressors in buildings, use clamp-on ferrites for protection on data cables and power cords; no shielded rooms are required (but recommended)

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Source: Electromagnetic Pulse (EMP) Protection Guidelines for Equipment, Facilities and Data Centers, Version 6.0, DHS 11 May 2015

Overall EMP Mitigation Conclusions

- The risk of not protecting critical infrastructures is profound
  - One HEMP burst can disrupt infrastructures across the continental USA
  - One SREMP burst can disrupt infrastructures within a 100 mile area
- EMP protection can be relatively low-cost for new equipment
  - 1% – 5% for terrestrial equipment/installations (more %$ for satellites)
  - EMP retrofit can be economical for surge protecting power/comms “tails”
- EMP protection guidance is needed for more than just HEMP
- Need massively scalable, cost-effective EMP mitigation programs to protect critical infrastructures

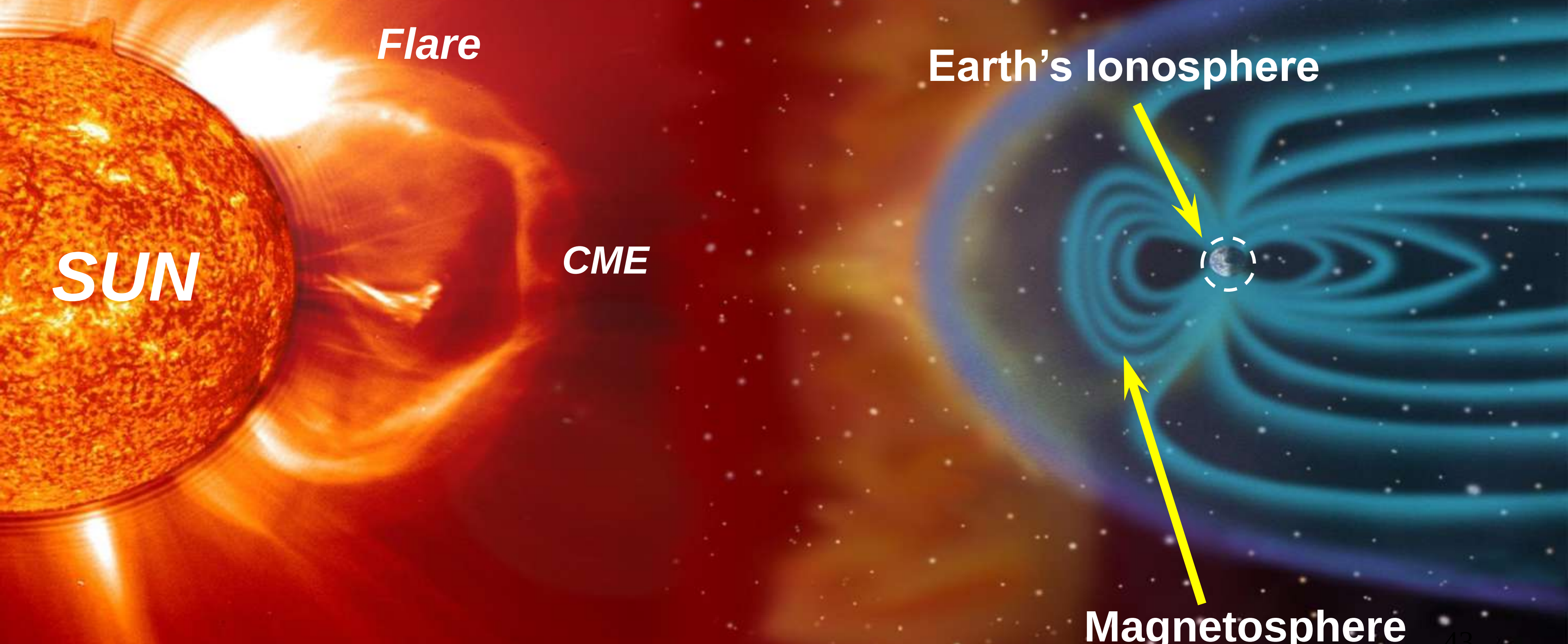
UNCLASSIFIED

Solar Superstorm Risks

What causes Solar Superstorms?

Answer: Explosions at the sun [93 million miles away] !

1. **Solar flares [photons arrive at earth within about ~ 8 minutes]**
2. **Solar protons and other charged particles [arrive ~ 20+ minutes]**
3. **Coronal mass ejections (CMEs) [arrive from ~ 14 to 96 hours]**



5/11/2015 K. Briggs. Graphic adapted from NOAA

43

Coronal Mass Ejections and the Earth
The biggest natural risk we face?

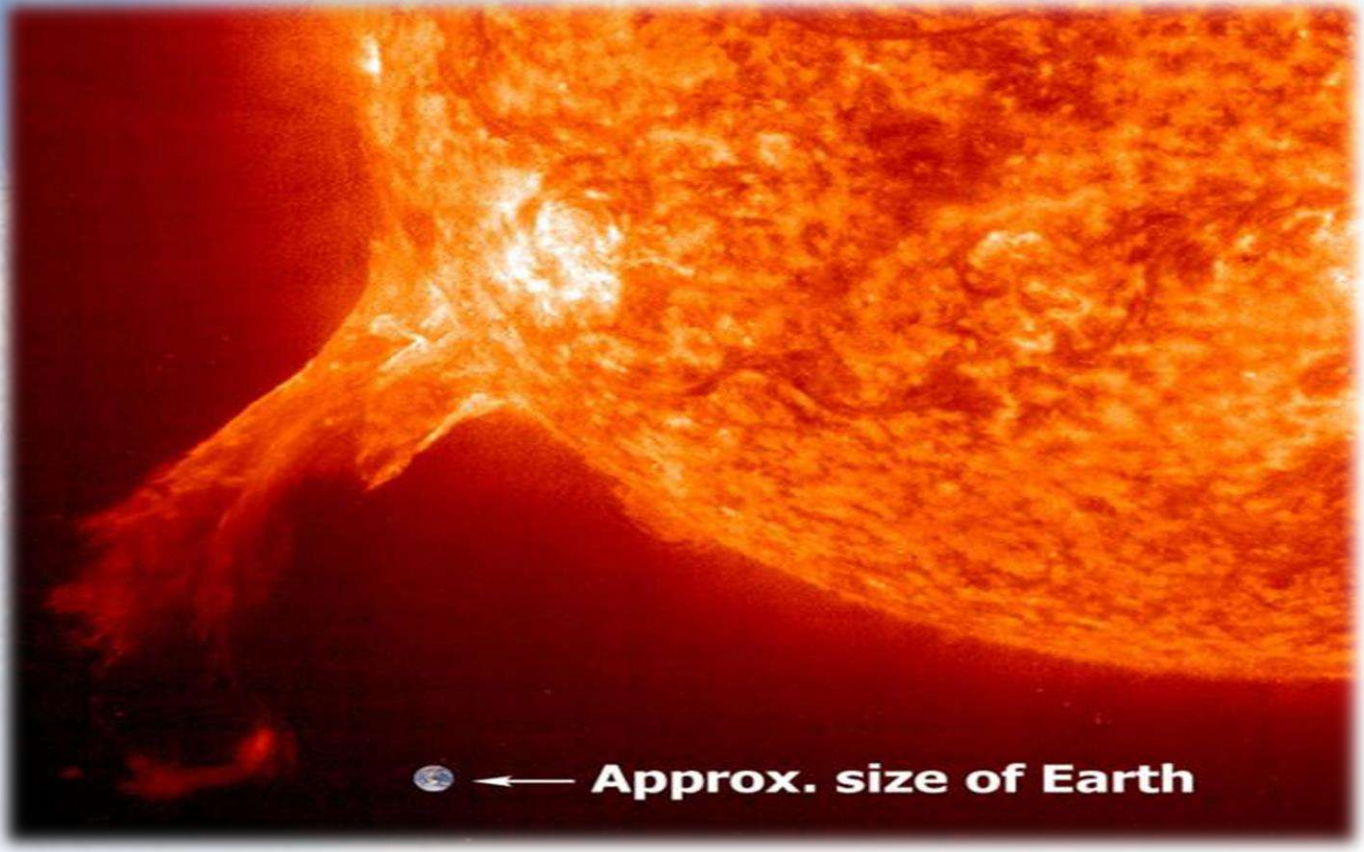


Image from the Solar and Heliospheric Observatory (SOHO) satellite shows an erupting coronal mass ejection, with an Earth inset at the approximate scale of the image. Credit: NASA www.nasa.gov/vision/universe/solarsystem/perfect_space_storm.html

Solar Superstorms: *Why worry?*
Dr. Holdren's Concerns

Celestial Storm Warnings, **NY Times, published on 10 March 2011**
By JOHN P. HOLDREN and JOHN BEDDINGTON
John P. Holdren *is the Science and Technology Adviser to President Obama*
John Beddington *was the Chief Scientific Adviser to Prime Minister Cameron*

"… From sporadic solar flares to ethereal shimmering aurora, manifestations of severe space weather **have the power to adversely affect the integrity of the world's power grids, the accuracy and availability of GPS, the reliability of satellite-delivered telecommunications and the utility of radio and over-the-horizon radar**."

"Space weather can affect human safety and economies anywhere on our vast wired planet, and blasts of electrically-charged gas traveling from the Sun at up to five million miles an hour can strike with little warning. **Their impact could be big — on the order of $2 trillion during the first year in the United States alone, with a recovery period of 4 to 10 years**."

In 1921, space weather wiped out communications and generated fires in the northeastern United States. **In March 1989, a geomagnetic storm caused Canada's Hydro-Quebec power grid to collapse within 90 seconds, leaving millions of people in darkness for up to nine hours**. In 2003, two intense storms traveled from the Sun to Earth in just 19 hours, causing a blackout in Sweden and affecting satellites, broadcast communications, airlines and navigation.

Bolding of text was not in the original.

Coronal Mass Ejections (CMEs) As seen on the earth as auroras

"Auroras are much more than just pretty lights in the sky. Underlying each display is a potent geomagnetic storm with possible side-effects ranging from satellite malfunctions in orbit to power outages on terra firma." – Tony Phillips, NASA

(from: www.nasa.gov/centers/goddard/news/topstory/2008/aurora_live.html)

An aurora in Alaska

Credit: Jan Curtis of the Geophysical Institute at the University of Alaska

from: www.nasa.gov/centers/goddard/news/topstory/2008/aurora_live.html

An aurora in Plymouth, OH

Credit: Terry Lutz

from www.nasa.gov/images/content/119657main_aurora_lg.jpg

Why should we be concerned about Solar Superstorms?

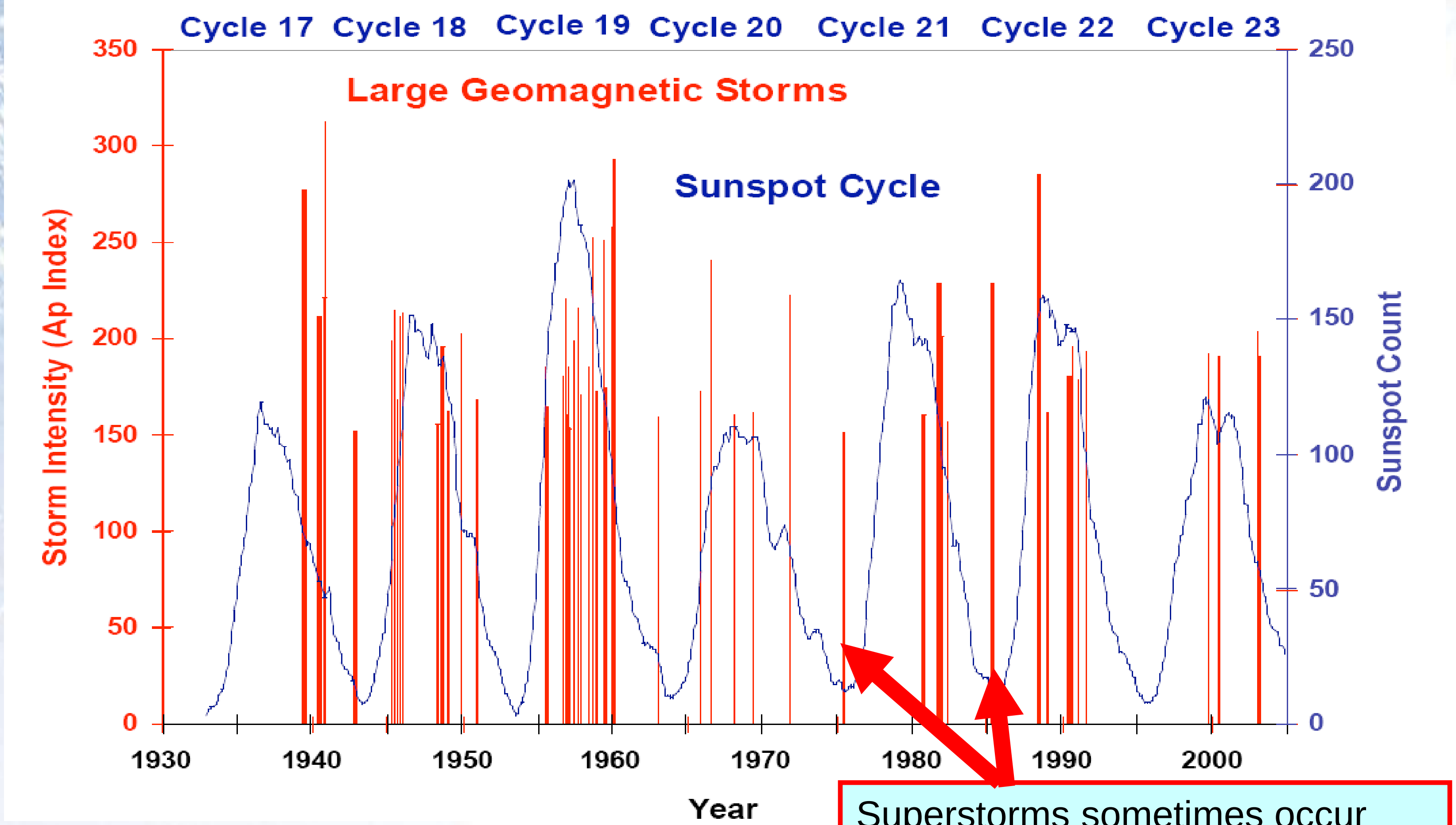
- Many experts believe it is highly likely that a Solar Superstorm could damage our power grid and leave much of the U.S. without power for days to years
- The power industry has only a very limited capability to protect the grid from solar superstorms (or from a related phenomena, electromagnetic pulse (EMP) attacks)
- Without power, all other infrastructures, like communications, quickly degrade/fail
- A black start of large portions of the US power grid may be required. Not easy.
- Without communications for the grid operators and SCADA*/control nets, restarting grid regions may be very difficult … need resilient communications
- Some key equipment needed to fix the grid, such as large generator step-up (GSU) transformers, are in short supply, require a long time to install, and may take well over a year to be delivered (especially if manufactured overseas)
- Long-term power outages could lead to a great loss of life due to a lack of food, water, and essential services

* SCADA = Supervisory Control and Data Acquisition

Solar Superstorms can occur at any time

Solar Superstorms denoted by red peaks

Sunspots count in blue



Superstorms sometimes occur when sunspot cycle is at a low

Near Miss: The Solar Superstorm of July 2012 and Storm Probabilities

- **From a 2014 NASA article**: "If an asteroid big enough to knock modern civilization back to the 18th century appeared out of deep space and buzzed the Earth-Moon system, the near-miss would be instant worldwide headline …
  - Two years ago, Earth experienced a close shave just as perilous, but most newspapers didn't mention it. The "impactor" was an extreme solar storm, the most powerful in as much as 150+ years. …
  - "If it had hit, we would still be picking up the pieces," says Daniel Baker of the University of Colorado.
  - "In my view the July 2012 storm was in all respects at least as strong as the 1859 Carrington event," says Baker. "The only difference is, it missed."
- In February 2014, physicist Pete Riley published a paper in Space Weather … In it, he analyzed records of solar storms going back 50+ years. By extrapolating the frequency of ordinary storms to the extreme, he calculated the odds that a Carrington-class storm would hit Earth in the next ten years. **The answer: 12%**"

http://science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm/

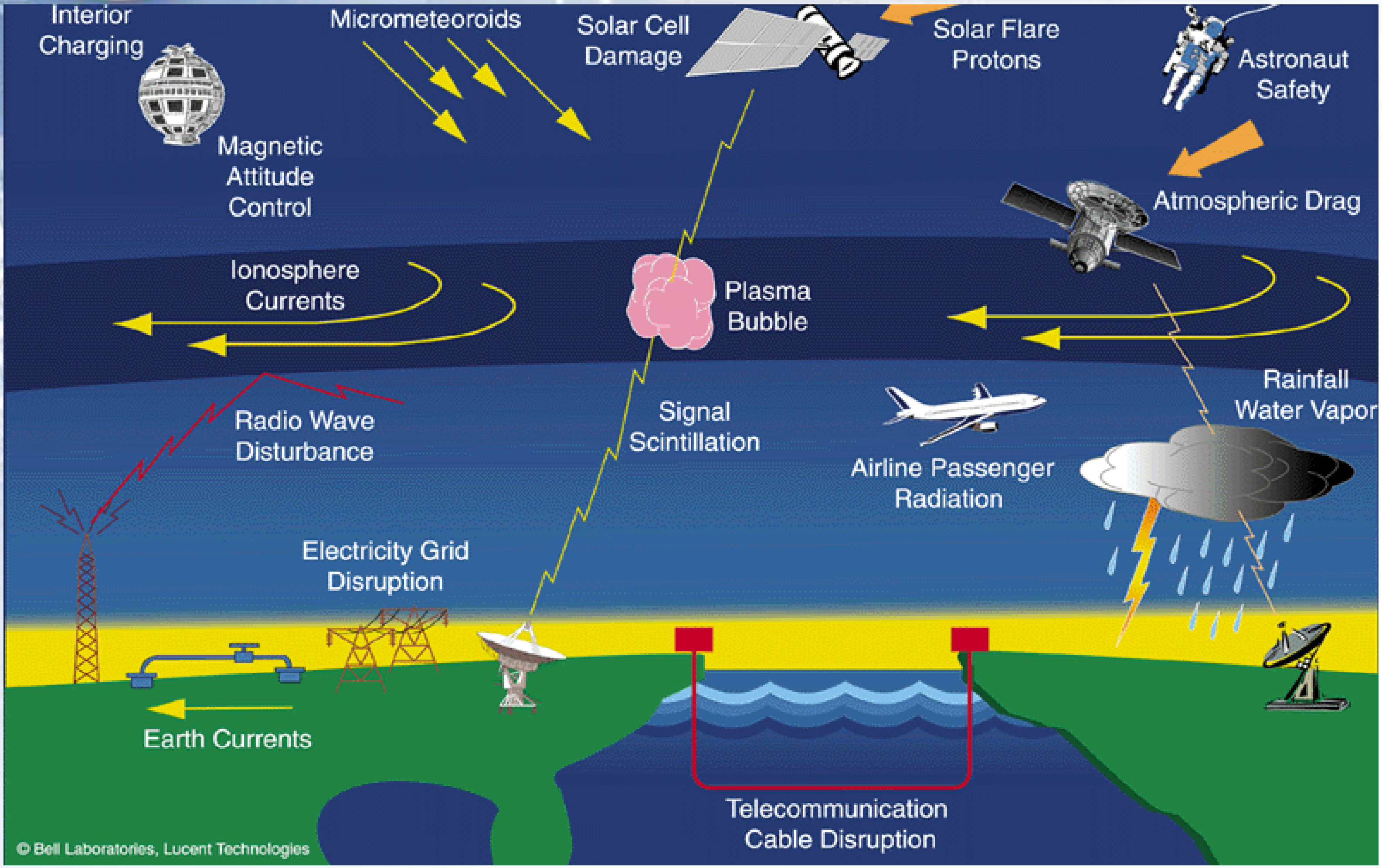
Solar Superstorm Probabilities/cont.

- One in 100 year storms (~4,800+ nT/min level over the USA)*
  - In the last 150+ years, only the 1859 and 1921 storms reached this level
  - Later slides show the potential impact of a 4800 nT/min storm
- One in 30 year storms (~2,400+ nT/min level over the USA)*
  - 1972 solar storm was last storm to approach this level over the USA
  - 1989 Hydro Quebec storm was at a lower level (max ~900 nT/min)
    - Much smaller than a "30-year" level storm
    - Transformers damaged: One at New Jersey's Salem nuclear plant; two La Grande 4 generating station step-up transformers in Canada
    - Caused collapse of Quebec's power grid for over 9 hours

Bottom line: Many experts believe we are due for a damaging, possibly catastrophic storm.

* From Ref 2, page 3-13, see Backup Slide

Systems that can be impacted by Solar Storms



Credit: NASA and Bell Laboratories, Lucent Technologies
www-istp.gsfc.nasa.gov/istp/outreach/images/Gusts/effects.gif [June 2008]

Space Weather Scales

http://www.swpc.noaa.gov/NOAAscales/

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yrs)
Scale	Descriptor	Duration of event will influence severity of effects		
		Radio Blackouts		
R 5	Extreme	**HF Radio:**Complete HF (high frequency**) radio blackout on t sunlit side of the Earth lasting for a number of hours. This result radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritim aviation systems experience outages on the sunlit side of the Ear hours, causing loss in positioning. Increased satellite navigation positioning for several hours on the sunlit side of Earth, which n into the night side.		
R 4	Severe	**HF Radio:** : HF radio communication blackout on most of the s Earth for one to two hours. HF radio contact lost during this tim **Navigation:** Outages of low-frequency navigation signals cause error in positioning for one to two hours. Minor disruptions of s navigation possible on the sunlit side of Earth.		
R 3	Strong	**HF Radio:** Wide area blackout of HF radio communication, los contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for abo		
R 2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sur of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals fo minutes.		
R 1	Minor	**HF Radio:** Weak or minor degradation of HF radio communica side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for bri		

* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, bu considered.
** Other frequencies may also be affected by these conditions.

Flares cause Radio Blackouts and use the “R” Scale

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yrs)
Scale	Descriptor	Duration of event will influence severity of effects		
		Solar Radiation Storms	Flux level	Number of
S 5	Extreme	**Biological:** unavoidable high radiation hazard to astronauts on E vehicular activity); high radiation exposure to passengers and cre commercial jets at high latitudes (approximately 100 chest x-rays **Satellite operations:** satellites may be rendered useless, memory cause loss of control, may cause serious noise in image data, star be unable to locate sources; permanent damage to solar panels po **Other systems:** complete blackout of HF (high frequency) comm possible through the polar regions, and position errors make navi operations extremely difficult.		
S 4	Severe	**Biological:** unavoidable radiation hazard to astronauts on EVA; radiation exposure to passengers and crew in commercial jets at (approximately 10 chest x-rays) is possible. **Satellite operations:** may experience memory device problems a imaging systems; star-tracker problems may cause orientation pr solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through th regions and increased navigation errors over several days are like		
S 3	Strong	**Biological:** radiation hazard avoidance recommended for astrona passengers and crew in commercial jets at high latitudes may rec radiation exposure (approximately 1 chest x-ray). **Satellite operations:** single-event upsets, noise in imaging syster reduction of efficiency in solar panel are likely. **Other systems:** degraded HF radio propagation through the pola navigation position errors likely.		
S 2	Moderate	**Biological:** none. **Satellite operations:** infrequent single-event upsets possible. **Other systems:** small effects on HF propagation through the pol navigation at polar cap locations possibly affected.		
S 1	Minor	**Biological:** none. **Satellite operations:** none. **Other systems:** minor impacts on HF radio in the polar regions.		

Solar particles cause Radiation Storms & use the “S” Scale

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yrs)
Scale	Descriptor	Duration of event will influence severity of effects		
		Geomagnetic Storms	Kp values* determined every 3 hours	Number of storm events when Kp level was met
G 5	Extreme	**Power systems:** : widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** may experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** weak power grid fluctuations can occur. **Spacecraft operations:** minor impact on satellite operations possible. **Other systems:** migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.	Kp = 5	1700 per cycle (900 days per cycle)

CME’s cause Geomagnetic Storms and use the “G” Scale

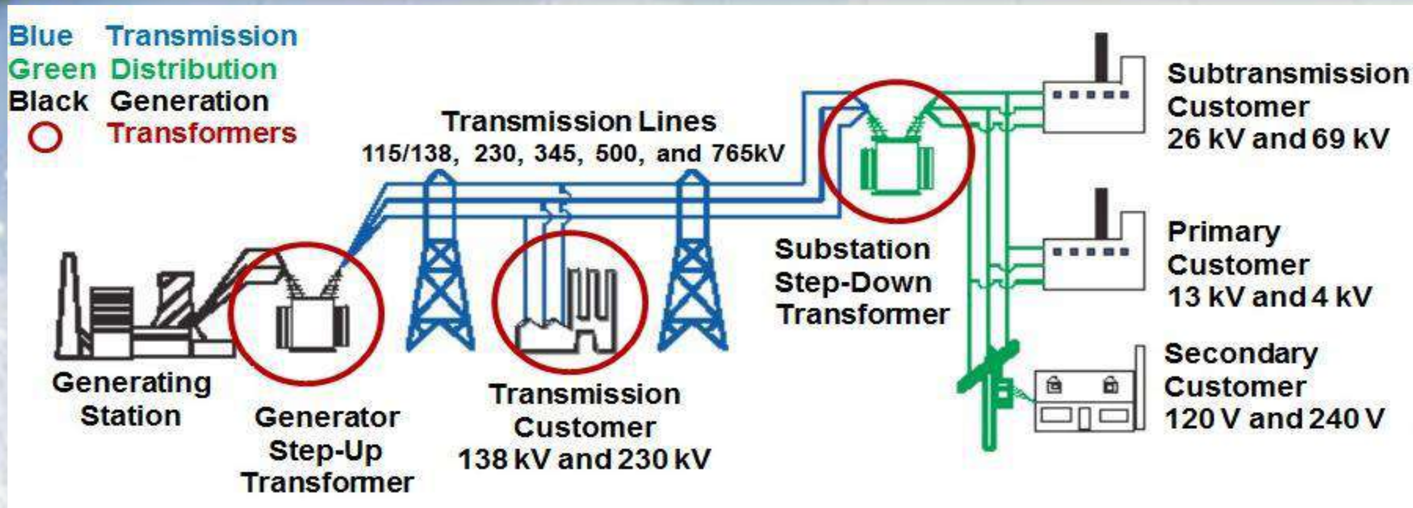
Examples of historical Solar Storm damage to infrastructure

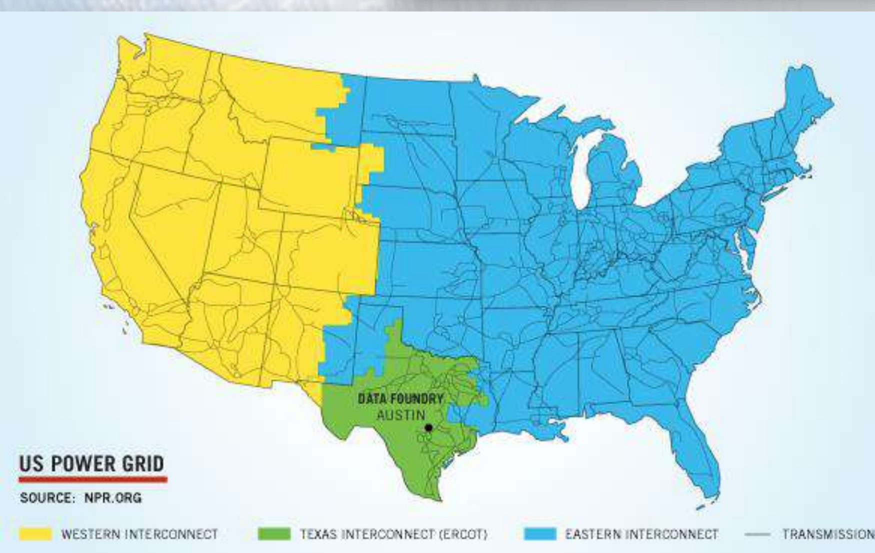
- **Satellites** [R1 and discussions with NOAA and other NASA and many news sources]
  - 1994: Anik E1 & E2 damaged (TV and data services lost to 1600 communities)
  - 1997: $200M Telstar 401 satellite failed during solar storm
  - 1998: PanAmSat's Galaxy IV satellite (disrupted pager service across USA)
  - 2003: Extensive satellite upsets (e.g. SOHO) and damage (ACE) due to storm
  - 2012: SkyTerra 1 (weeks of outage) and Spaceway 3 (restored next day)
- **Power grid** (especially Extra High Voltage (EHV) transformers) [R1/2/9]
  - 1958 & 1972: Transformer failures at British Columbia Hydro & Power Authority
  - 1989: Hydro Quebec power failure; Salem NJ nuclear plant transformers failed
  - 2003: 14 transformers damaged in South Africa [R1 and R2, page 3-25]
- **Long communications lines** [R1/2/5/9]
  - 1859, 1882, 1909, 1921, 1926: Telegraph fires/shocks
  - 1940 & 1958: Landline / undersea lines disrupted
  - 1972: US and Canada’s telephone system disrupted

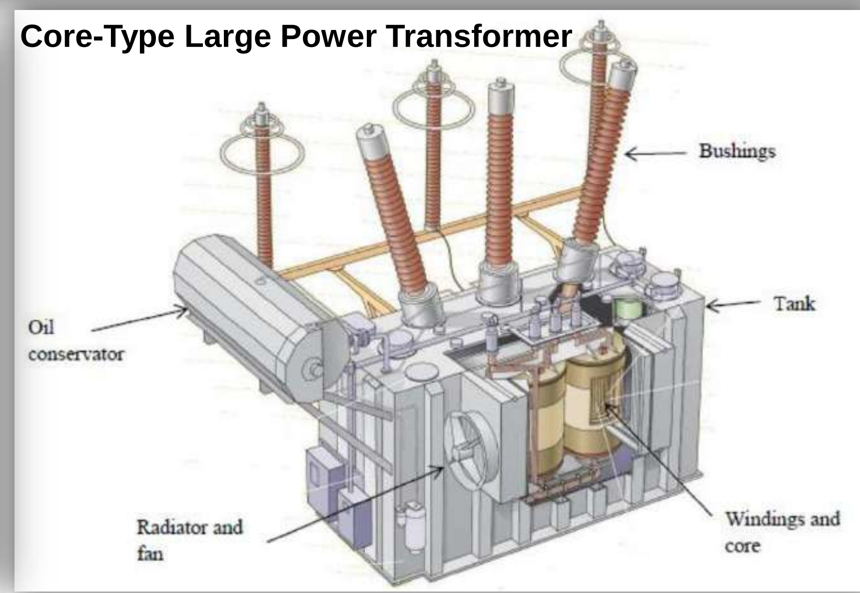
Damaged Salem NJ nuclear plant transformer http://science.nasa.gov/headlines/y2008/06may_carringtonflare.htm

Key Elements of U.S. Power Grid

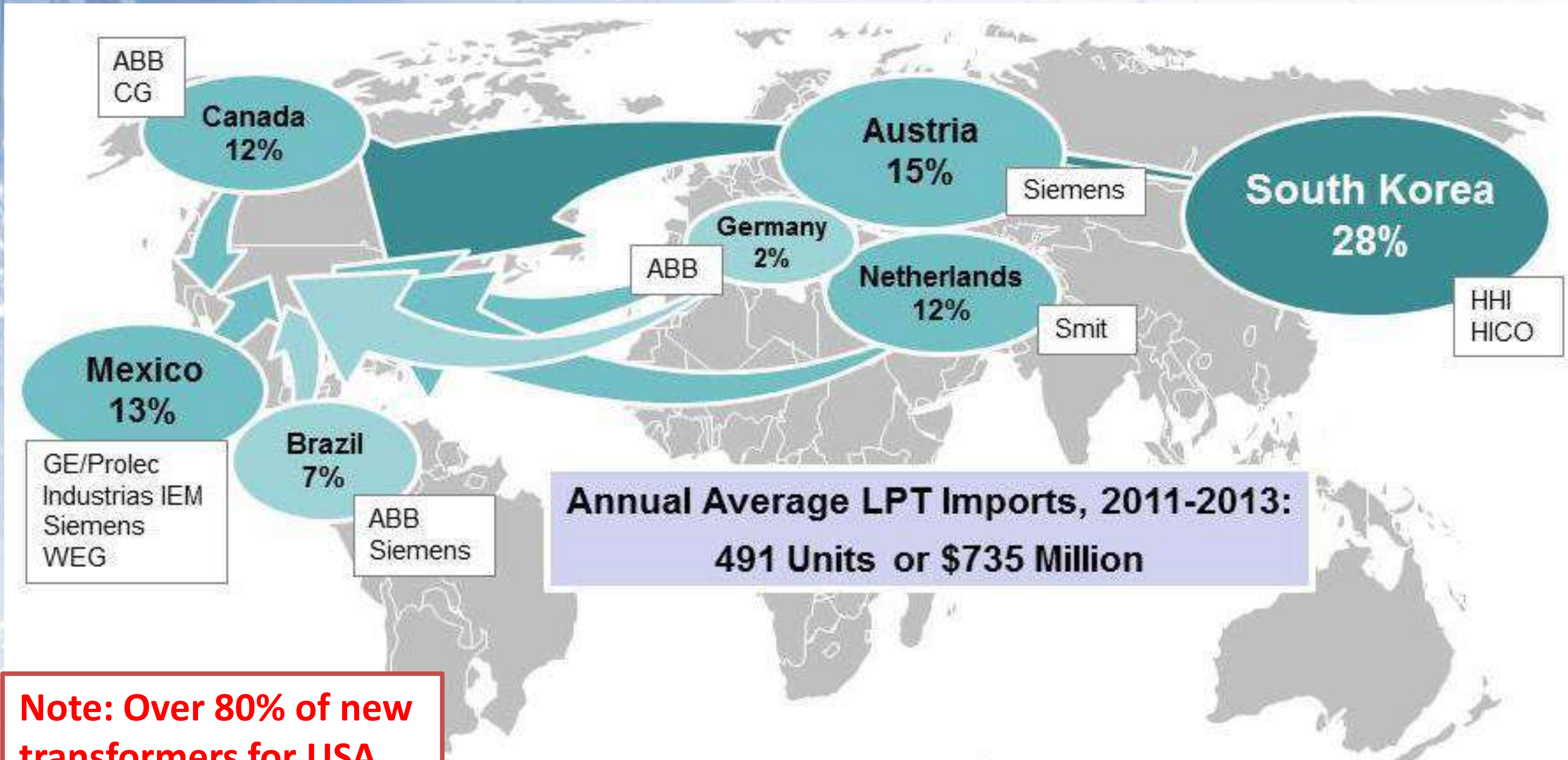
Sources
Right: Large Power Transformers and the U.S. Electric Grid**,** DOE
Bottom Right: "Liquid-Filled Power Transformers" ABB







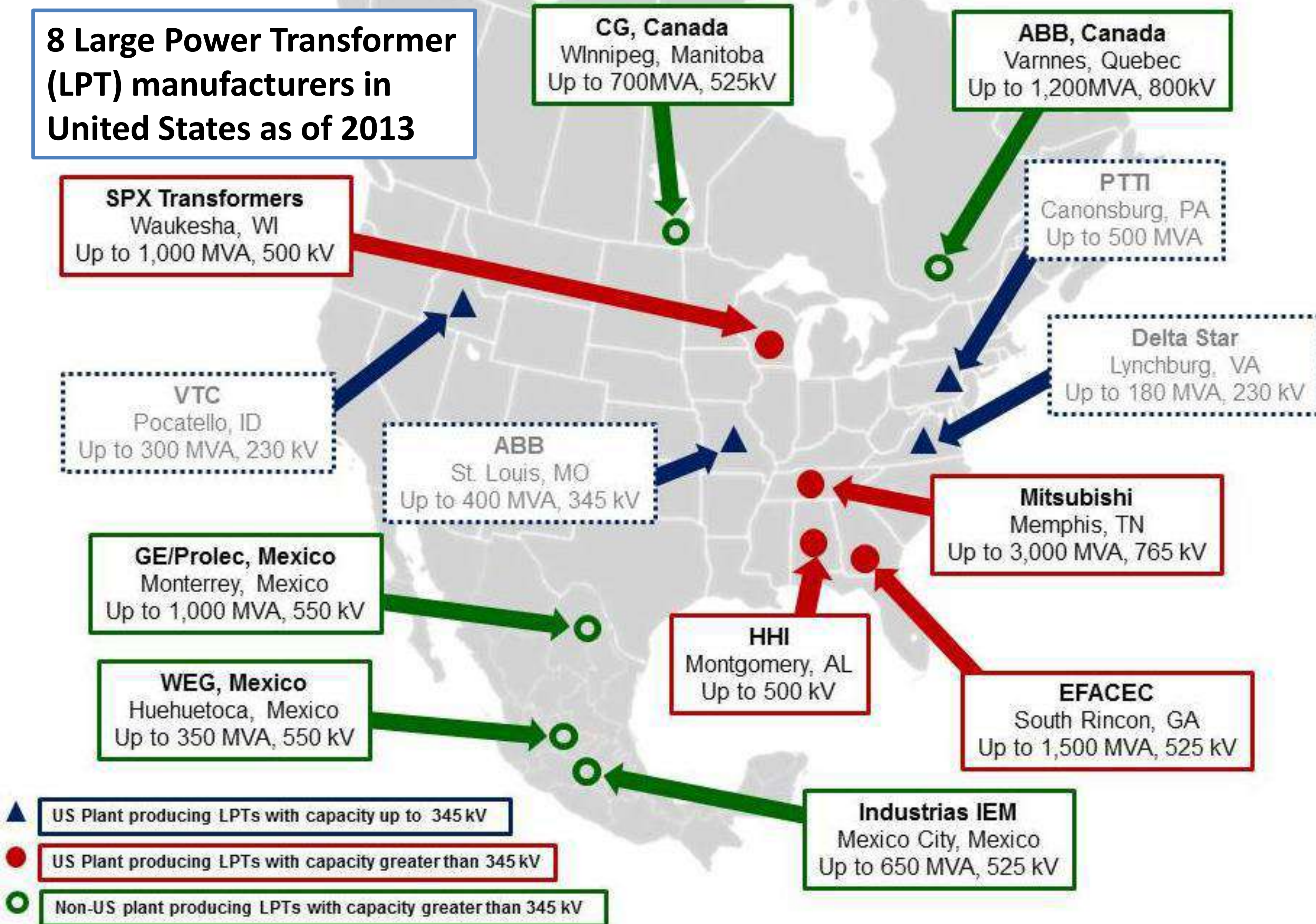
Global Suppliers of Large Power Transformers to the USA from 2011 - 13



Note: Over 80% of new transformers for USA were purchased from foreign sources in 2010.

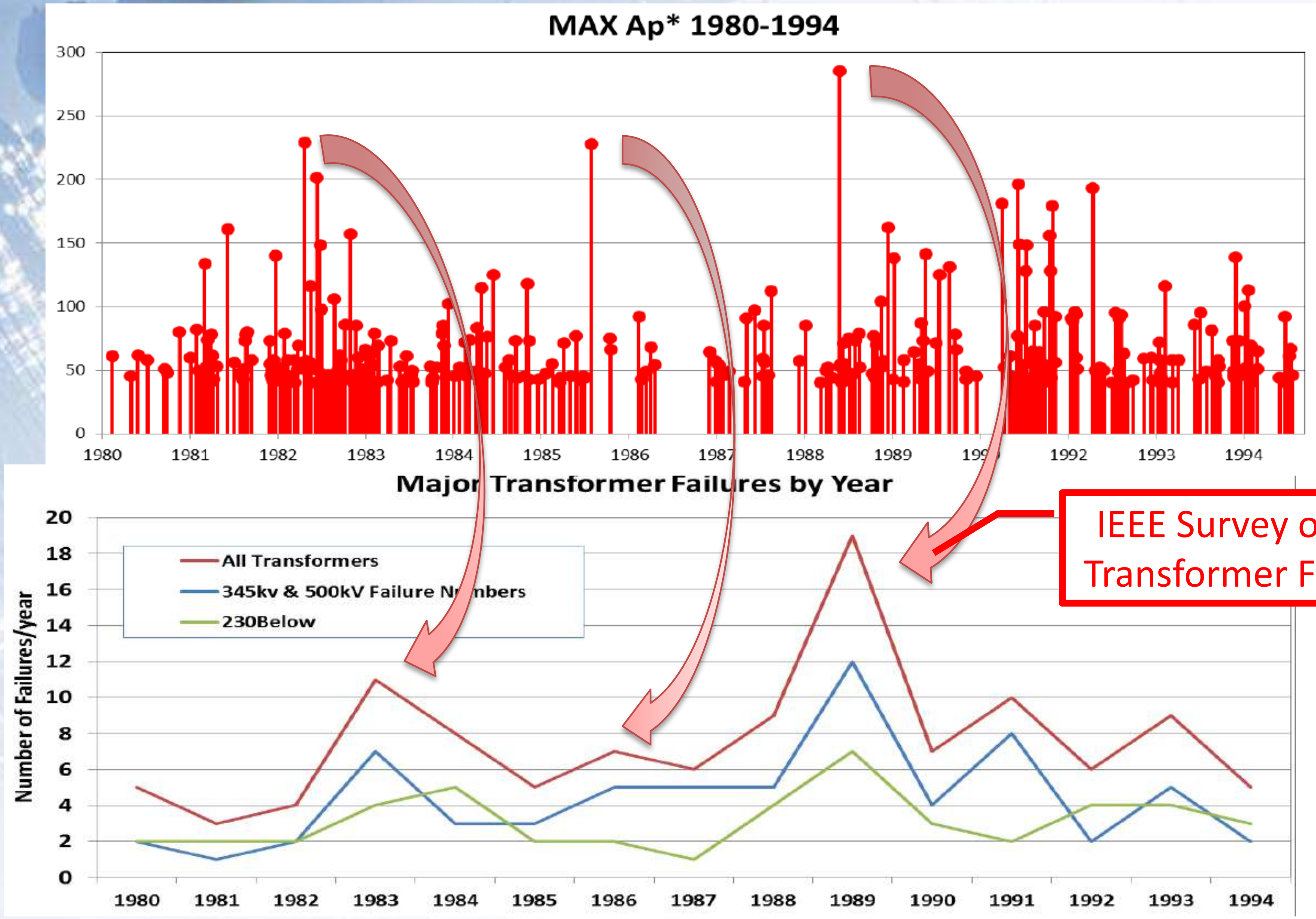
Note: This analysis includes LPTs with capacity greater than or equal to 100 MVA.

8 Large Power Transformer (LPT) manufacturers in United States as of 2013



Source: ICF International

Solar Superstorms & Transformer Failures – Trends

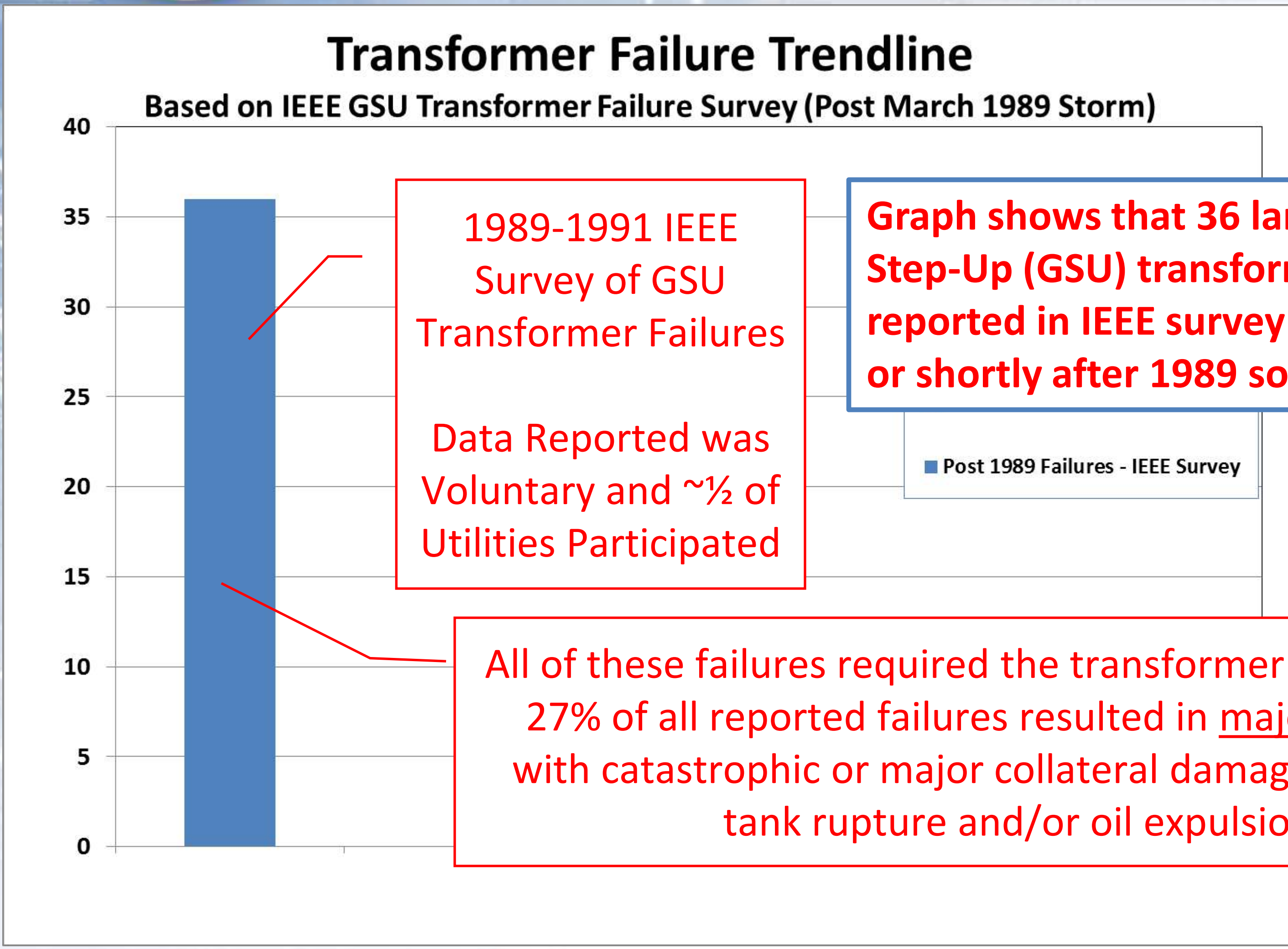


Two graphs show a strong correlation between solar superstorms & transformer failures

IEEE Survey of GSU Transformer Failures

Source: Graphic adapted from "An Overview of Emerging Power Industry Standards for Geomagnetic Storms" by John Kappenman

Solar Superstorms & IEEE Survey's Transformer Failures – 1989 - 1991



1989-1991 IEEE Survey of GSU Transformer Failures

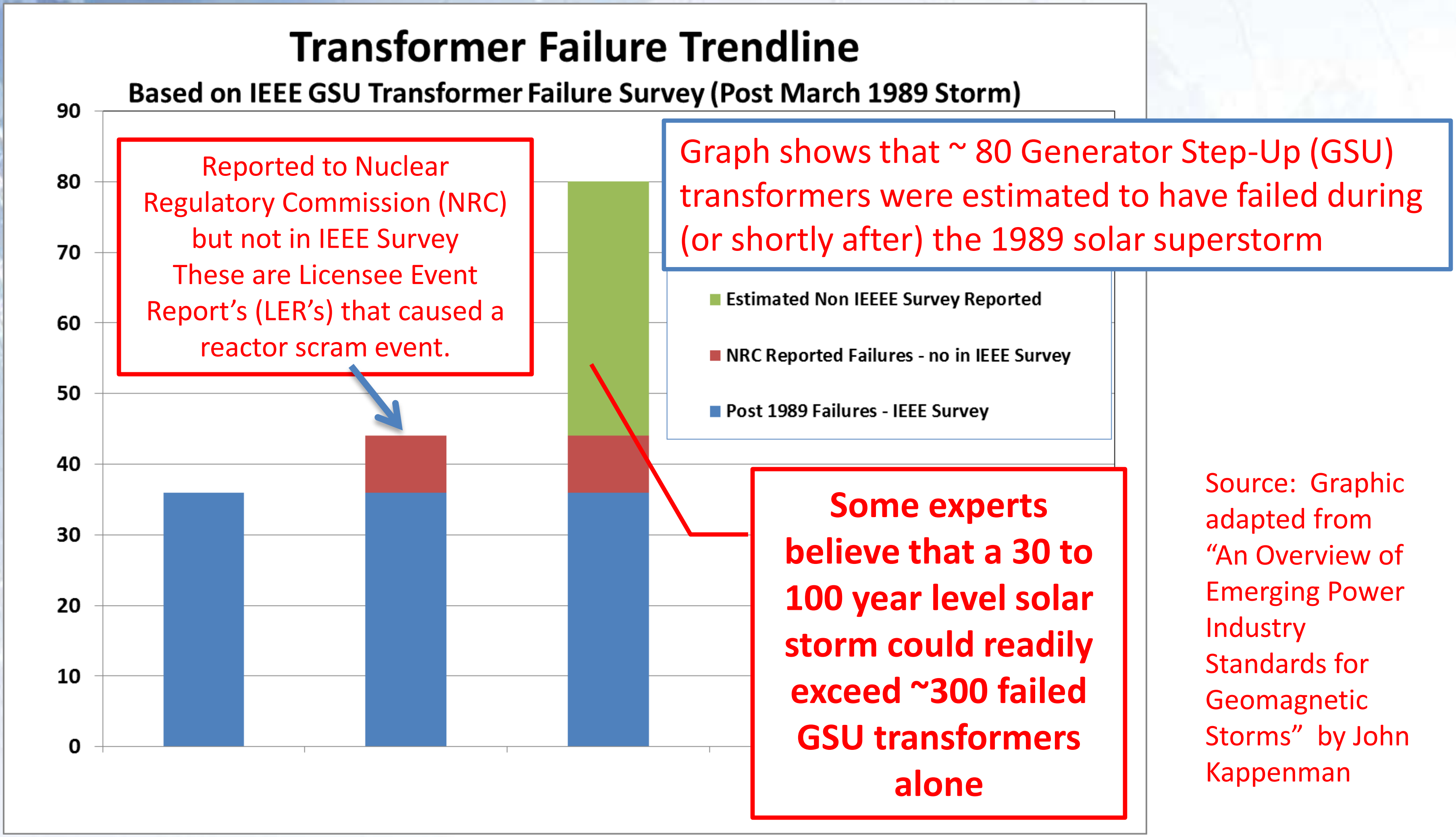
Data Reported was Voluntary and ~½ of Utilities Participated

Graph shows that 36 large Generator Step-Up (GSU) transformers were reported in IEEE survey that failed during or shortly after 1989 solar superstorm

All of these failures required the transformer to be replaced. 27% of all reported failures resulted in <u>major fire events</u> with catastrophic or major collateral damage due to fires, tank rupture and/or oil expulsion.

Source: Graphic adapted from "An Overview of Emerging Power Industry Standards for Geomagnetic Storms" by John Kappenman

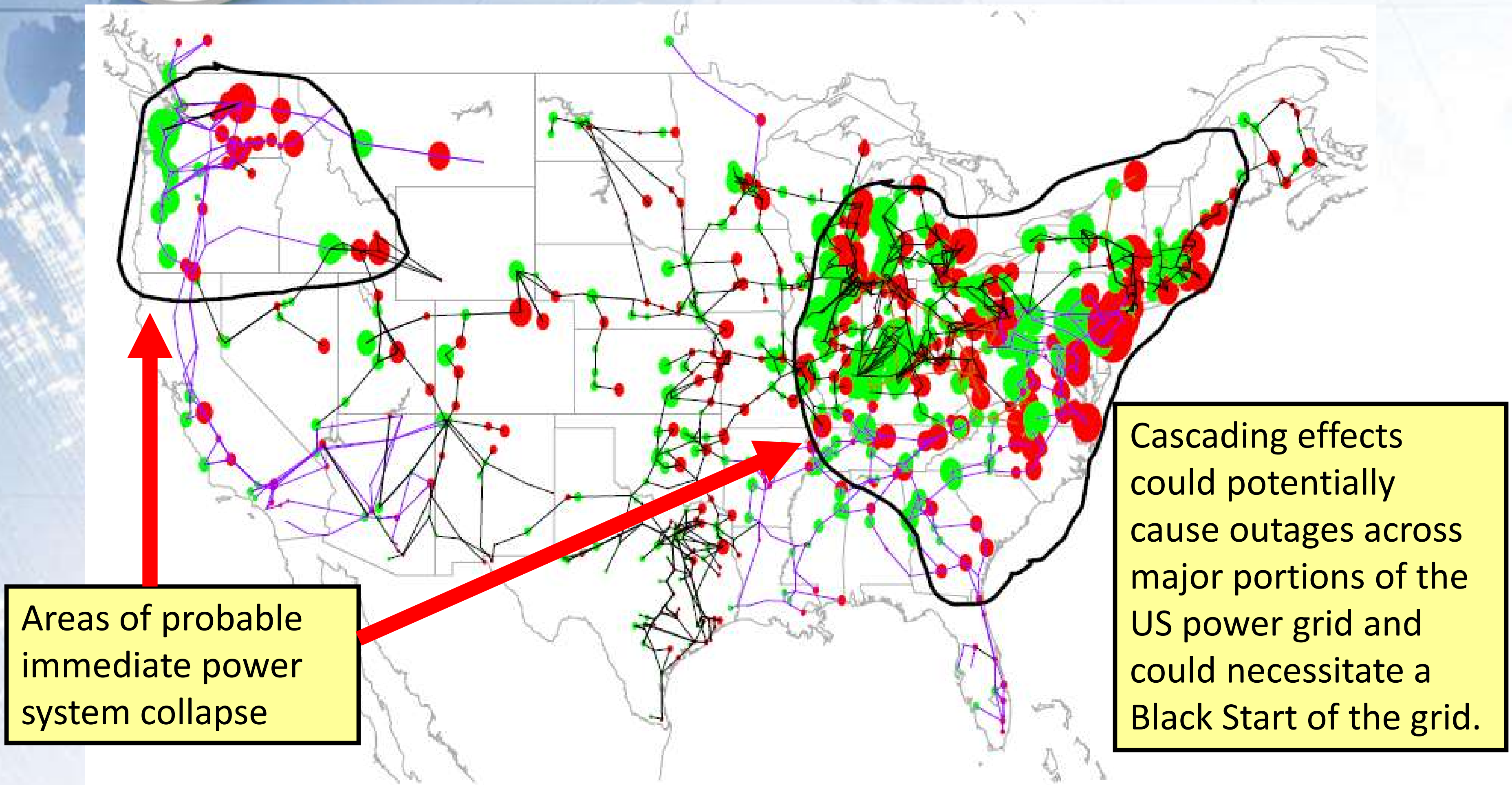
IEEE + NRC Reported Transformer Failures after 1989 storm (1989 – 1991)



Source: Graphic adapted from "An Overview of Emerging Power Industry Standards for Geomagnetic Storms" by John Kappenman

FEMA 2008 Scenario Results (part 1)

presented at National Academies Workshop, 23 May 08



100 Year Geomagnetic Storm – 50 Degree Geomagnetic Disturbance Scenario

FEMA Solar Superstorm Study Results
Grid Transformer Damage (45°N scenario)

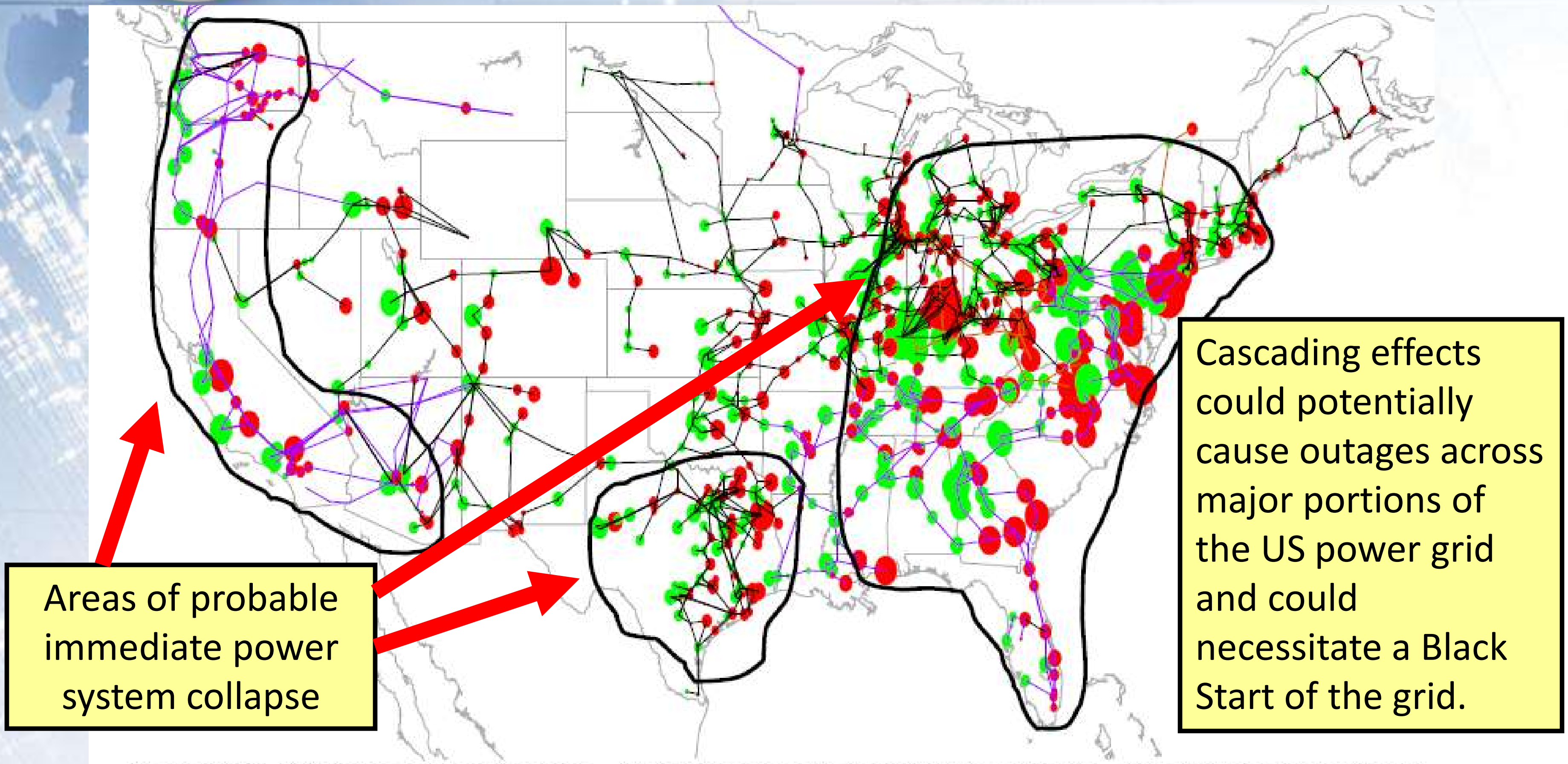


Figure 3-26. 100 Year geomagnetic storm – 45 degree geomagnetic disturbance scenario. The above regions outlined are susceptible to system collapse due to the effects of the GIC disturbance.

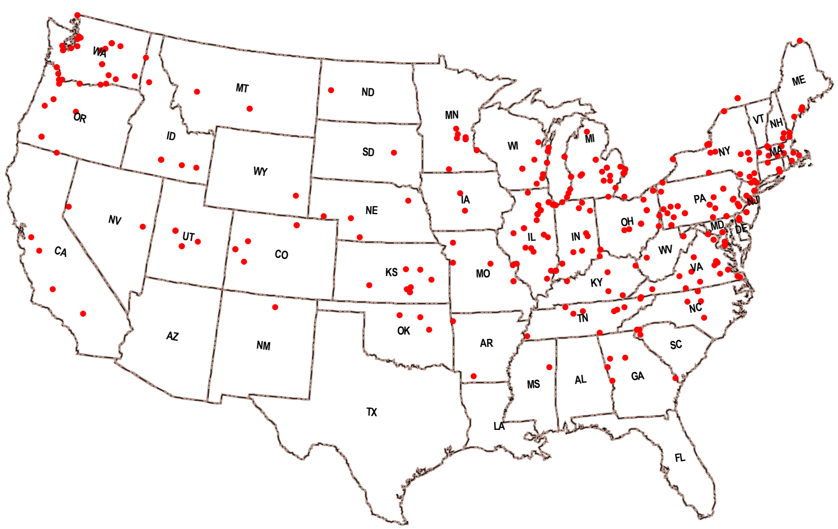
From: "An Assessment of the Threat Potential to the US Electric Power Grids from Extreme Space Weather Storms – Analysis of US Power System Impacts from Large Geomagnetic Storm Events" by John Kappenman and Peter Warner, Metatech Corporation, in support of a FEMA sponsored contract with Cubic Applications, Inc., 1 Oct 2007 (Meta-R-295) [R2]

FEMA Solar Superstorm Study Results for Grid Transformer Damage (50°N scenarios)

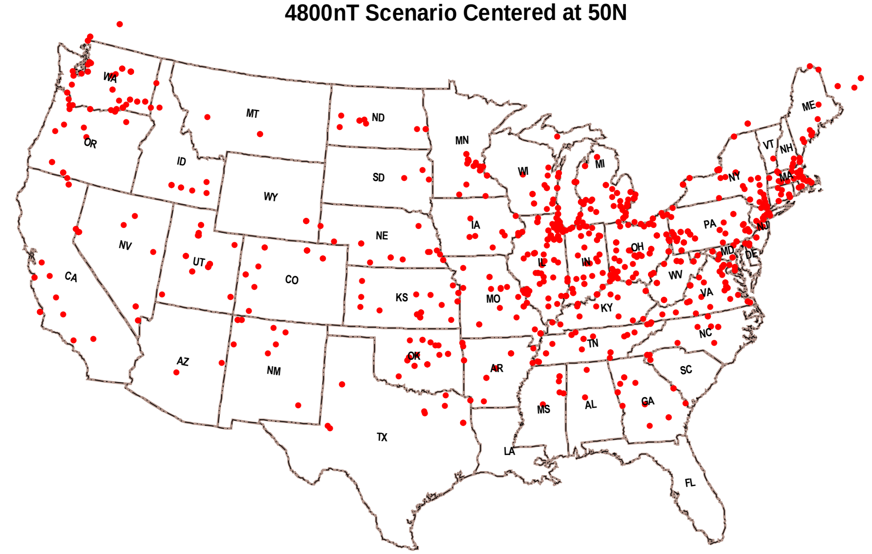
If transformers fail at GIC over 90A:
~640 Transformers Damaged

If transformers fail at GIC over 30A:
~1,000 Transformers Damaged

US Grid Map with Effective GIC Over 90A
4800nT Scenario Centered at 50N



US Grid Map with Effective GIC Over 30A
4800nT Scenario Centered at 50N



Even the Medium Damage Scenario May Take ~10 Years to Replace All Damaged EHV other Large Power Transformers (LPTs)

From: “Economic Analysis of a Major Geomagnetic Storm on the United States” – Briefing provided by Cubic Applications, Inc., 8 February 2008 [R4]

Communications Dependencies on Commercial Power

- **Wireless**
  - Cell sites have 4 to 8 hours of backup power. Some cell sites have access to generators, including key cell towers & cells on roofs of buildings with generators
  - Mobile Switching Centers (MSCs) typically have up to 72 hours of backup power
  - Both MSCs and cell sites with diesel generators will have power for as long as fuel can be delivered to the facilities
- **Wireline / Cable**
  - Typical Central Offices have up to 72 hours of backup power on site and generators that can maintain operations for as long as fuel can be delivered
  - Remotes have up to 8 hours of on site backup power; some have generators
  - Plain telephone handsets can be powered directly from the Central Office
  - Most telephones use commercial power to operate (with limited battery backup)
  - Cable –based voice equipment typically has from 4 to 12 hours of backup power
- **Emergency Alert System (EAS) Primary Entry Point (PEP) Radio Stations**
  - 30+ days of on-site fuel and good radio coverage over most of the US population

Warning of Extreme Solar Events
Lessons from the 2015 St. Patrick's Day Storm

- **Background from NASA**
  - On Sunday, March 15, a coronal mass ejection exploded off the Sun towards Earth, as observed by NASA and National Oceanic and Atmospheric Administration (NOAA) instruments. By March 17, the burst of solar particles and energy reached Earth and kept the solar wind stream at potent levels for more than 24 hours. The storm reached a G4 or "severe" level on NOAA's geomagnetic storm scale, and the Kp index—a metric for global geomagnetic storm activity—fluctuated between 6 to 8 on a scale that goes to 9. The "northern lights" reached as far south as the central and southern United States.
- **Lessons from Event**
  - **NOAA predicted a G1 level storm … but storm surprised forecasters … went to a G4**
  - **Arrived ~ 7 hours earlier than expected**
  - **NOAA emphasized to DHS that they cannot reliably predict CME arrival time & levels**
  - **Some power companies didn't realize there was a G4 storm until DHS told them**
  - **We should not trust that power companies will have adequate warning to react to any geomagnetic storm and hence have time to enact grid protection procedures**

Solar Superstorms vs Other Risks

[note: ranking is arbitrary within each cell]

Level 1 - Extreme - $ Trillion(s) lost	- Extreme pandemic (<< 1%) - Extreme volcanic (Yellowstone, etc. << 1%) - Extreme meteor (<< 1%)	6. Solar Superstorm (100 year level: 4800+ nT/min) (since 1921 storm, > 58%) 7. Simultaneous nuclear detonations in ≥ 2 cities 8. Regional HEMP* attack via nation-state or state supported terrorists	1. Solar Superstorm (30 year level: 2400 nT/min) (since 1972 storm, >70%) 2. Extreme cyber attack 3. CONUS HEMP* attack 4. Extreme biological attack 5. Nuclear detonation in one large US city
Level 2 - Major to Severe - $ Millions to Billion(s) lost	- 7.6 + New Madrid earthquake (~10%) - Severe volcanic event like Mount St. Helens near population center (includes lahars, etc.) - Major pandemic (~ 1%)	15. Nuclear terrorism - 10kT Improvised Nuclear Device 16. Nation-state sponsored cyber terrorist attack 17. 6.3 NMSZ* quake (> 63%) 18. Tactical RF* Weapons 19. Bombs (thermobaric, etc.) 20. Internet & EAS* disruptions	9. Floods/Tsunamis (>99%) 10. Severe hurricane (>99%) 11. Major cyber attack 12. Major CA earthquake in LA or Bay Area (~88%) 13. Severe biological attack 14. Low yield nuclear attack on key city (10 kT or less)
Impact Scale ↑ 1. Likely? (Natural)	**For natural disasters:** **≤ 50% chance in 30 years**	**For natural disasters:** **50% - 70% chance in 30 years**	**For natural disasters:** **> 70% chance in next 30 years**
Or **2. Capable? (Manmade)**		**For manmade disasters:** **Near-term capability: nations or state-supported terrorists**	**For manmade disasters:** **Current capability for nations or state-supported terrorists**

*** See note page for definitions**

What can be done? (part 1)

- **Need communications, security, transportation, & supplies to restore power**
  - **Need backup fuel and generators that support communications for 30+ days**
    - Ensure backup generators can support both communications equipment and supporting equipment, like heating and cooling
    - If do not store fuel on site or have renewable power (for example, wind or solar), must ensure external fuel suppliers can pump fuel without commercial power for weeks or months
  - **Restoration will likely require communications that don't rely on the commercial Internet and phone networks**
    - HF long-range voice and data communications may prove key to restoration
      - Resilient voice and data networks like SHARES may prove key to restoring essential services/power
    - UHF/VHF Land Mobile Radio (LMR) important for local communications
    - Public switched voice (both landline and cellular) & Internet likely to be disrupted
      - Priority services like GETS, WPS, and TSP may prove key for using limited voice and data services
    - Satellites may be significantly disabled/damaged due to solar superstorm effects

What can be done? (part 2)

- **Need to protect key power grid elements in USA and Canada**
  - **Over 2,000 Extra High Voltage (EHV) Transformers**
  - **Tens of thousands of other Large Power Transformers (over 100 MVAs)**
  - **About 6,000 power plants (100 nuclear reactors and large hydro plants are key)**
  - **About 50,000 electric substations in the USA**
  - **Experts have recommended protecting neutrals in LPTs from GICs**
    - Large resisters in neutrals could work but may increase problem for non-protected equipment and resisters don't effectively mitigate harmonics
    - Capacitors in the neutrals can protect equipment from both GICs and harmonics (appears to be a better solution than resisters)
    - Neutral disconnect switch during times of major storm (but leaves LPTs vulnerable to ground faults)
    - One hybrid solution, the Emprimus SolidGround™ neutral DC blocking system, has been tested and proved to be effective by the U.S. government

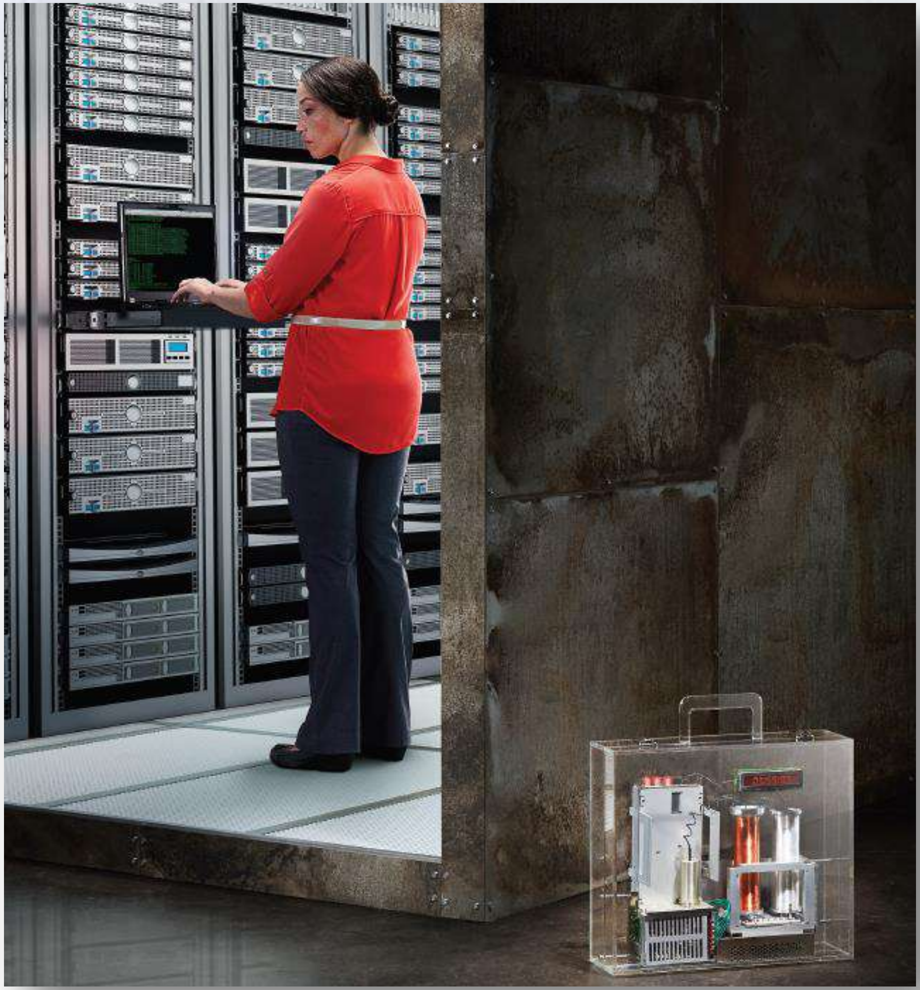
What can be done? (part 3)

- **Risk and costs to mitigate** **(Preliminary estimate. For some alternate estimates, see www.resilientsocieties.org/economicsofresiliency.html)**

Worst-case ratio of deaths in USA if 100 year level solar superstorm	Total # of U.S. deaths due to solar storm	Economic life value in $ USD	Loss in $USD based solely on number of deaths in USA	Scenario: Weather Season when storm strikes
1 out of 1,000 die	318,900	$ 7,000,000	$ 2,232,300,000,000	Spring and Fall
1 out of 100 die	3,000,000	$ 7,000,000	$ 21,000,000,000,000	Summer
1 out of 10 die	30,000,000	$ 7,000,000	$ 210,000,000,000,000	Winter

Key elements to protect the U.S. grid	Number	Cost to protect	Total Cost to Protect (in $USD)
Top 2,000 EHV transformers	2,000	$ 350,000	$ 700,000,000
Top 20,000 substations	20,000	$ 400,000	$ 8,000,000,000
100 nuclear reactor sites	100	$ 1,000,000	$ 100,000,000
Top 650 largest hydro plants	650	$ 1,000,000	$ 650,000,000
HF & satellite voice/email between key sites	3,000	$ 50,000	$ 150,000,000
Federal, state, & local grid protection grants			$ 400,000,000
Total			**$ 10,000,000,000**

Intentional Electromagnetic Interference (IEMI) and Radio Frequency (RF) Weapons



[Graphic source: IEEE Spectrum Sep 2014]

Worldwide Scientific Activity in IEMI

- URSI published a resolution in 1999 dealing with the criminal activities of EM "tools" and the need to protect against the threat
- The International Electrotechnical Commission (IEC) SC77C (EMC: High Power Transient Phenomena) is writing standards to deal with this problem in general (new project on IEMI immunity tests)
- ITU-T has developed a recommendation on dealing with HPEM threats (IEMI) on telecommunications systems (K.81: Nov. 2009)
- The IEEE EMC Society published a special issue on IEMI in August 2004 and is working on a standard to protect publicly accessible computers from IEMI (P1642)
- Many EMC and HPEM Conferences are dealing with IEMI (~ 3 per year)
- Private companies are developing methods of threat assessments, protection methods, and monitors
- Fear of Frying: IEEE Spectrum, Sep 2014

[Source: Adapted from Metatech briefing for DHS]

Briefcase Mesoband Generator

- 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)
  - Modified versions produce higher directional outputs
  - 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 and new version is 4 times more powerful

[Source: Metatech briefing for DHS]

JOLT IRA Hyperband Emitter

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

[Source: Metatech briefing for DHS]

Internal Voltage Level Examples

Induced Peak Voltages for Measurement Sites										
Location		Parameters			Peak Cable Voltage, kV					
		Shld	Cbl	R	Worst Case Cable (1%)			Average Cable (50%)		
						IEMI			IEMI	
Site	Room	dB	m	m	HEMP	Severe	Moderate	HEMP	Severe	Moderate
Substation	Comm	20	3	110	14.90	98.41	9.84	9.0	25.87	2.59
	345 kV Relay	30	3	110	7.95	4.32	0.43	4.80	2.00	0.20
				255	2.51	1.37	0.14	1.52	0.63	0.06
	161 kV	25	3	130	2.51	0.59	0.06	1.52	0.27	0.03
Control Center	Comm	20	3	10	4.47	2.06	0.21	2.70	0.95	0.10
	Control	20	10	30	7.95	47.55	4.76	4.80	22.05	2.21
	EMS	15	3	10	26.50	29.17	2.92	16.00	7.67	0.77
Back-Up Power Facility	Control	25	3	5	14.14	84.56	8.46	8.54	39.21	3.92
				20	4.47	53.48	5.35	2.70	24.80	2.48
	Generator 1	20	10	10	4.47	13.37	1.34	2.70	6.20	0.62
				20	26.50	87.50	8.75	16.00	23.00	2.30
	Generator 2	25	10	10	26.50	43.75	4.38	16.00	11.50	1.15
				30	14.90	49.20	4.92	9.00	12.93	1.29
	Generator 3	15	10	10	14.90	16.40	1.64	9.00	4.31	0.43
				20	14.90	49.20	4.92	9.00	12.93	1.29

[Source: Metatech briefing for DHS]