ELECTROMAGNETIC PULSE (EMP) AND IT'S EFFECTS

January 10, 2017

2015 Testimony of Dr. Peter Vincent Pry, EMP Commission Member – before a Joint House Committee of Congress

- "Natural EMP from a geomagnetic super-storm, like the 1859 Carrington Event or 1921 Railroad Storm, or Nuclear EMP attack from terrorists or rogue states, are both existential threats that could kill up to **9 of 10 Americans** through **starvation, disease, and societal collapse**. A natural EMP catastrophe or nuclear EMP attack could blackout the national electric grid for months or years and collapse all the other critical infrastructures – communications, transportation, banking and finance, food and water – necessary to sustain modern society and the lives of 310 million Americans".

Outline

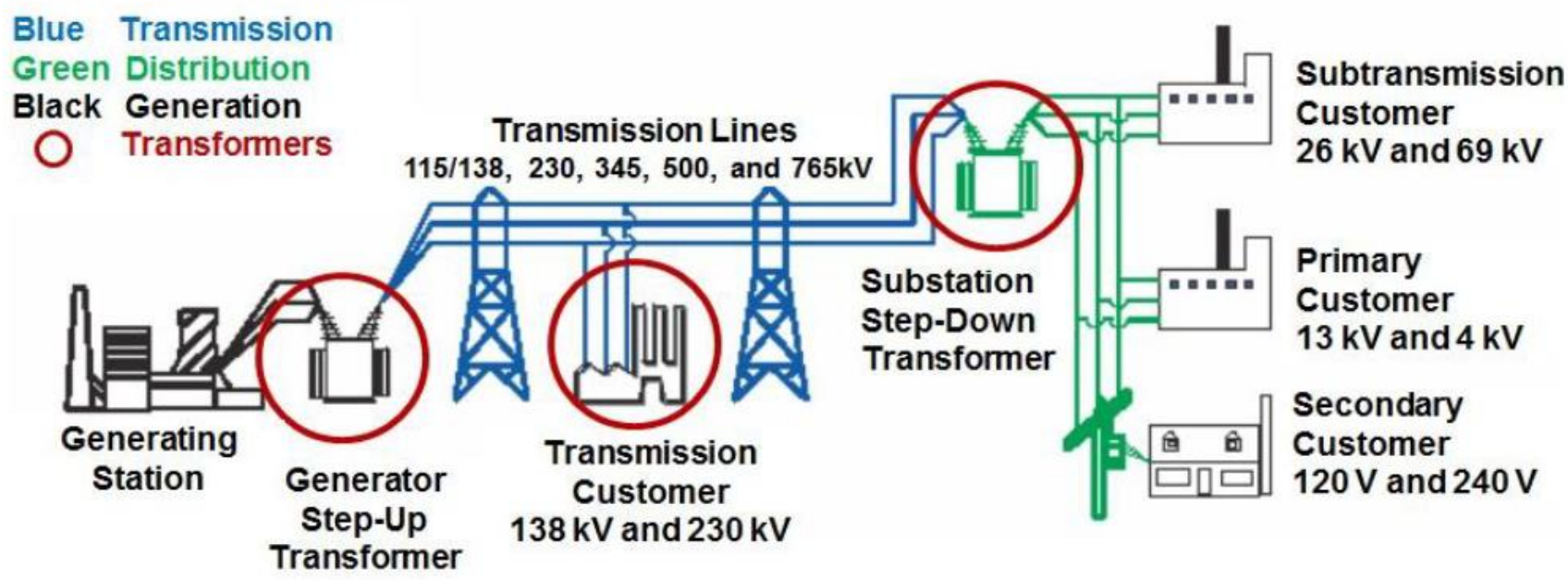
- EMP Description and Sources
- Nuclear Weapon generated EMP
- Nuclear Weapons
- Nuclear Players
- Effects of Nuclear EMP on Power Grid
- Solar Storms
- Effects of Solar Storms on Power Grid
- Intentional Electromagnetic Interference (IEMI)
- Power Grid Description
- References

What is an EMP?

- EMP is an intense Broadband Burst of Electromagnetic Energy
  - Several Sources for EMP
  - Damages electronics by inducing voltages and/or currents far above what they were designed to withstand
  - Couples with long power lines to generate thousands of volts in power lines
- Focus of this Presentation
  - EMP and its effects on the U.S. Power Grid
  - This is the PRIMARY EMP threat to the U.S.

U.S. Electric Grid Representation

Figure 1. Electric Power Grid Representation



Source: DOE, 2006; see Footnote 14. Modified based on industry review.

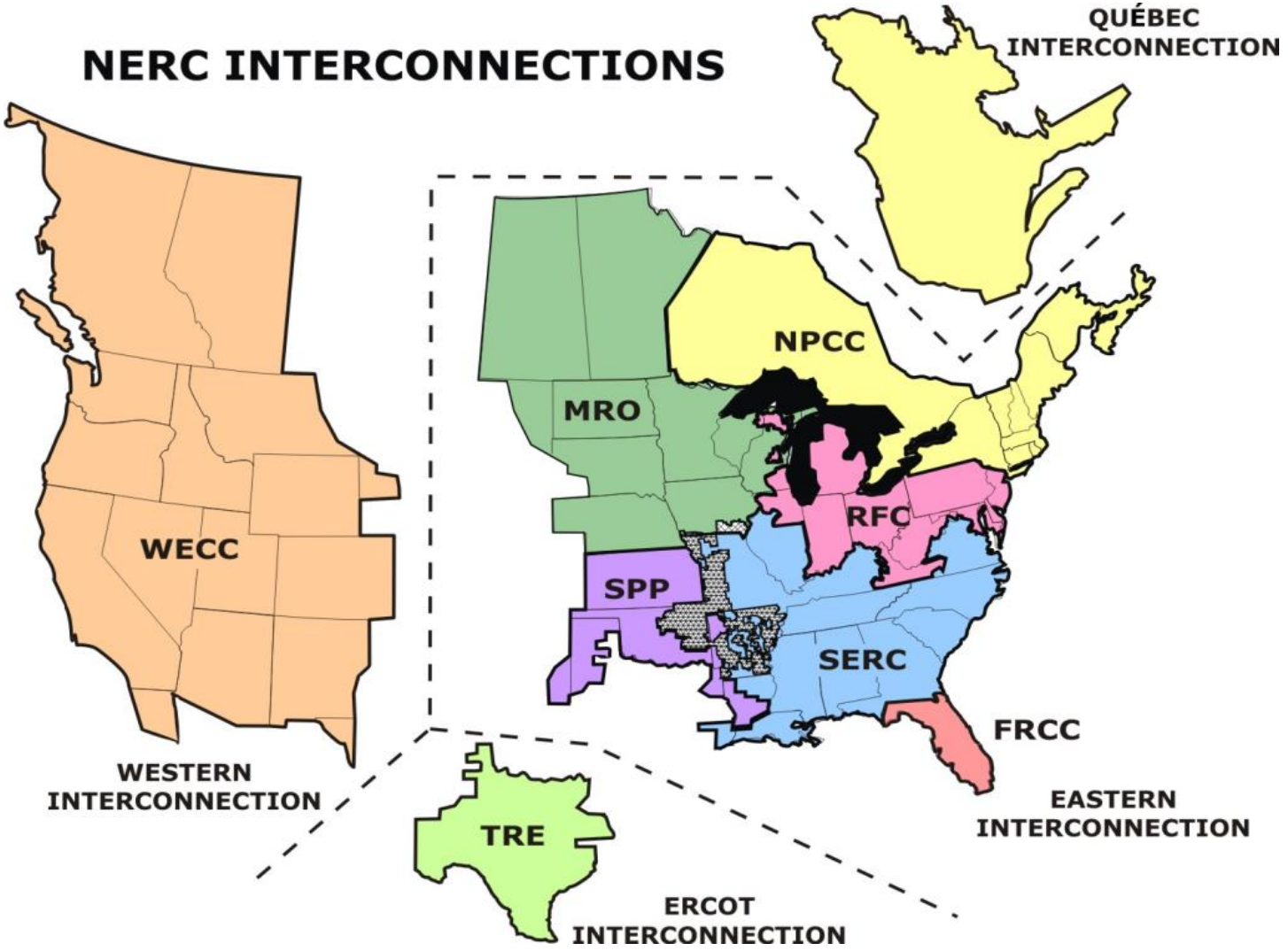
Example of EHV Transformer

Figure 4. Transport of Large Power Transformers

Note: Workers move wires, lights, and poles to transport a 340-ton power transformer, causing hours of traffic delay.

Source: Pittsburgh Live News, December 2011.

NERC Interconnections



What would a Terrorist or Rouge Country try to do in an EMP Attack

- Take down as much of the U.S. Power Grid for as long as they could
  - Nationwide Power outage for 1+ years is possible
    - Regional outage would allow some normalcy, supplies, communication, repair parts to flow into affected areas and help to keep our Government and Economy functioning
  - Most every Infrastructure in the U.S. depends on availability of Electricity
    - One scenario takes out all electronic systems
    - Worst scenario takes out all electronic systems and also destroys several Large Power Transformers (LPT's) which are imported and have 1+ years lead time

Comparison of Various Sources for EMP (16)

Source	Frequencies	Field Strength	Area of Affect	Maturity	Notes
Low-Altitude Nuclear Burst	Wideband (3Hz – 1 GHz)	Very High (100 kV/m at surface	Medium (To 14 miles)	High	Detonated below 25 miles altitude
High-Altitude Nuclear Burst (HEMP)	Wideband (3Hz – 1 GHz)	High (10-50 kV/m at surface	Large (1,500+ mile radius)	High	Detonated at an altitude between 25 and 300 miles
Solar Storm			Could be all of No. America	N/A	Coronal Mass Ejection from Sun
IEMI (Intentional Interference)	Narrow or Wideband	Low (5-200 V/m at target	Small (100's of meters)	Med	Terrorist or Criminal. Military is a separate subset of IEMI
EMP Test Equip & Military	Various	To 50 kV/m	10's of meters	High	Usually large in size

Some Examples of EMP in History

- Operation Starfish –
  - US High Altitude Test in 1962 over Johnson Island
  - 1.44 MT Burst at 240 miles Height of Burst (HOB)
  - 900 Miles away in Hawaii
    - Street Lights Blown out
    - Telephone and Radio communications affected
- USSR Test 184 over Kazakhstan 10/22/1962
  - 300kT, HOB 290 km (180 miles)
  - Lots of instrumentation and data analysis
  - Knocked out 1000 km underground power line
  - E3 component at U/G power cable was 1300 nT/min
  - Induced 1500 to 3400 amperes in long overhead telephone line
  - USSR ran 25 such EMP tests over large populated land mass

Black Swans [7]

POTENTIAL BLACK SWANS THAT WOULD CAUSE THE GREATEST DISRUPTIVE IMPACT	
Severe Pandemic	No one can predict which pathogen will be the next to start spreading to humans, or when or where such a development will occur. An easily transmissible novel respiratory pathogen that kills or incapacitates more than one percent of its victims is among the most disruptive events possible. Such an outbreak could result in millions of people suffering and dying in every corner of the world in less than six months.
Much More Rapid Climate Change	Dramatic and unforeseen changes already are occurring at a faster rate than expected. Most scientists are not confident of being able to predict such events. Rapid changes in precipitation patterns—such as monsoons in India and the rest of Asia—could sharply disrupt that region's ability to feed its population.
Euro/EU Collapse	An unruly Greek exit from the euro zone could cause eight times the collateral damage as the Lehman Brothers bankruptcy, provoking a broader crisis regarding the EU's future.
A Democratic or Collapsed China	China is slated to pass the threshold of US$15,000 per capita purchasing power parity (PPP) in the next five years or so—a level that is often a trigger for democratization. Chinese "soft" power could be dramatically boosted, setting off a wave of democratic movements. Alternatively, many experts believe a democratic China could also become more nationalistic. An economically collapsed China would trigger political unrest and shock the global economy.
A Reformed Iran	A more liberal regime could come under growing public pressure to end the international sanctions and negotiate an end to Iran's isolation. An Iran that dropped its nuclear weapons aspirations and became focused on economic modernization would bolster the chances for a more stable Middle East.
Nuclear War or WMD/Cyber Attack	Nuclear powers such as Russia and Pakistan and potential aspirants such as Iran and North Korea see nuclear weapons as compensation for other political and security weaknesses, heightening the risk of their use. The chance of nonstate actors conducting a cyber attack—or using WMD—also is increasing.
Solar Geomagnetic Storms	Solar geomagnetic storms could knock out satellites, the electric grid, and many sensitive electronic devices. The recurrence intervals of crippling solar geomagnetic storms, which are less than a century, now pose a substantial threat because of the world's dependence on electricity.
US Disengagement	A collapse or sudden retreat of US power probably would result in an extended period of global anarchy; no leading power would be likely to replace the United States as guarantor of the international order.

Low Altitude Nuclear

- HOB less than 25 miles (Stratosphere or lower)
- Electric and Magnetic Fields are extreme (100 kV/m)
- Gamma rays ionize nearby air molecules to create intense field
- EMP Area of Affect
  - Damage to Electronics and Electrical Grid out to 14 miles
  - Voltage spikes in wires to out to 70 miles
  - Fireball may reach surface causing physical damage and radiation (called Source Region EMP)
- Used against a Military Installation or City
- Would clearly be considered as a Nuclear Attack
  - US will probably be able to determine source of attack and retaliate accordingly

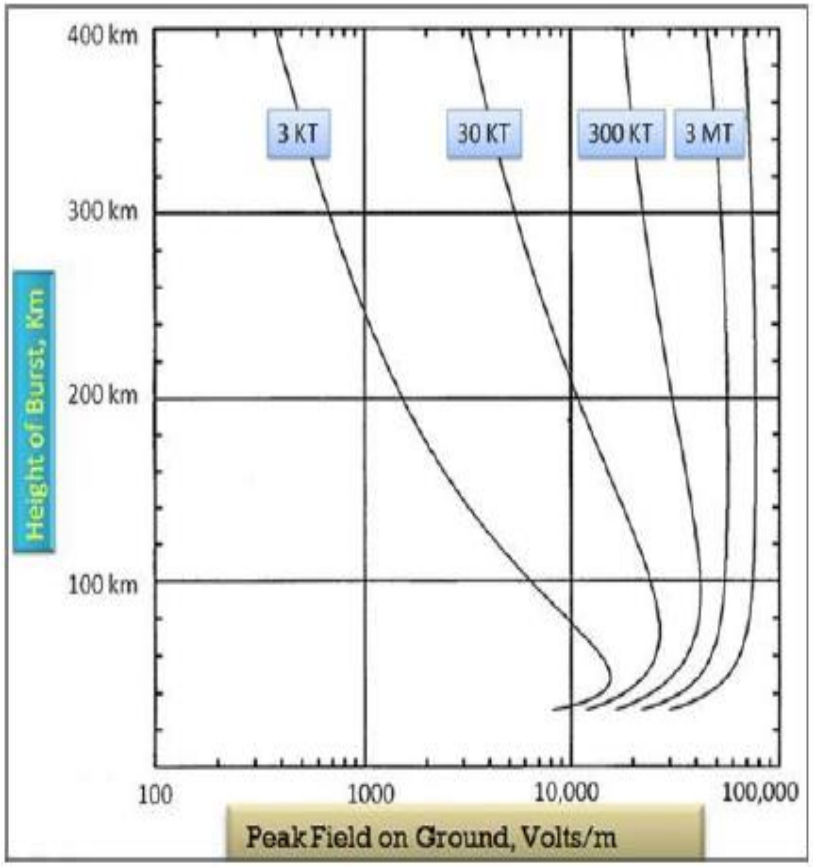
High Altitude Nuclear Explosion (HEMP)

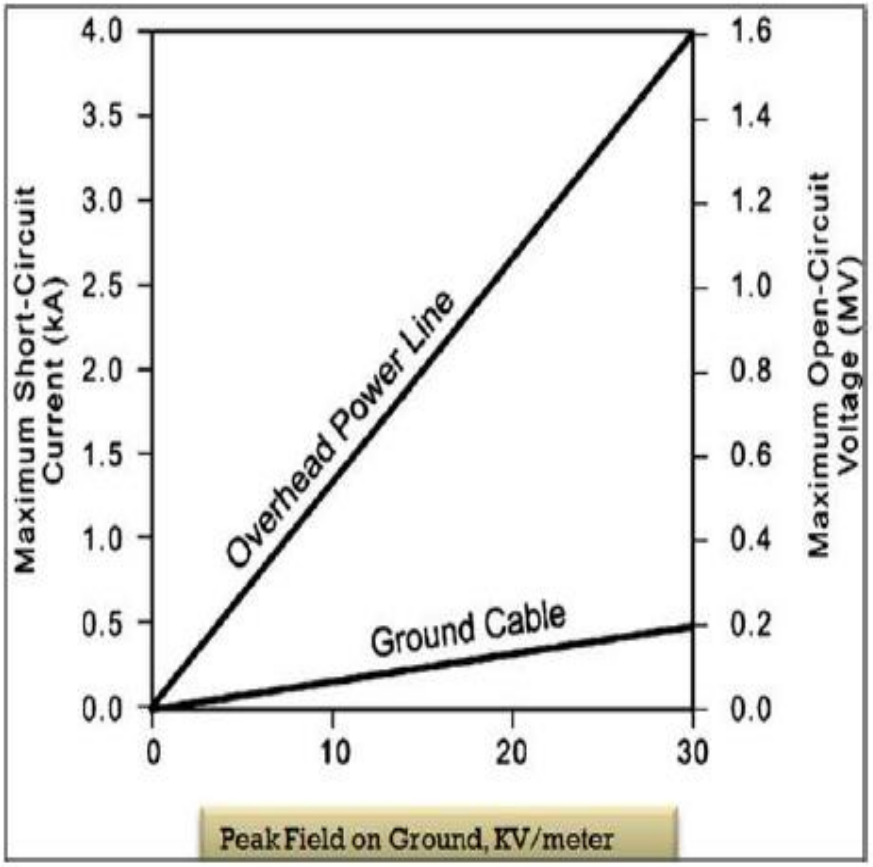
- Nuclear Weapon Detonation 25 to 300 miles in altitude
  - Above Stratosphere
- Affected area on surface of earth is “Line of Sight”
- Much of Information and Data on Nuclear Weapons and their tests remains “Classified”
  - This has lead to lots of “Guesstimation” and “Myths” about EMP
- Magnitude of EMP depends on:
  - Height of Burst (HOB)
  - Weapon Yield (and Type of Nuclear Reaction)
  - Construction Details of Weapon
  - Local strength of Magnetic Field (Latitude)
- Pulse has wide frequency range (1 Hz to 1 GHz)
- Not Harmful to Humans or Animals on surface of Earth
  - No sound, no radiation on surface, bright flash is only indication
- Two main “Types” of EMP
  - E1 (Fast Pulse)
  - E3 (Slow Pulse)

HEMP E1 PULSE

- Gamma Rays from Nuclear Explosion strip electrons from air molecules in Stratosphere (Compton Effect)
  - These electrons (negative charge) travel at near the speed of light
  - Electrons interact with earths magnetic field lines to produce pulse of EM energy on surface of Earth
- Peak of pulse occurs at 5 nanoseconds (5×10^{-9} seconds)
  - Pulse is over at 1,000 nanoseconds (1 microsecond)
  - Typical Peak Pulse on Earth (30^{o}-50^{o} Lat.) is 50 kV/m (6.6 megawatts/m^2)
    - Super EMP Weapons classified but 200 kV/m is speculated
  - For Fission Devices, Pulse at outer extremes of area is $50\%^{+}$ of Peak
  - Induced current is Thousands of Amperes
  - Pulse affects Short Line electrical and most unprotected electronic systems (SCADA, Personal electronics and computers, communication lines)
- E2 Pulse
  - 1 microsecond to 1 second – similar to Lightning – E1 is worse so little attention paid to E2

E1 Pulse vs. Weapon Yield
(Right Graph is E1 for Less than 10 kT Weapon)





HEMP E3 Pulse

- Lasts 100's of seconds to 1,000's of seconds
- Expanding Fireball and rising of heated and ionized layers of ionosphere "Distort" Earths Magnetic Field Lines and this (and Field Snapback) causes E3 component
  - Referred to as Magnetohydrodynamic (MHD) EMP
  - Coronal Mass Ejection (CME) from Sun (Solar Storm) is very similar in effect
- E3 induces 100's to 1,000's of amps in long conducting lines (few km's)
- Affects long line network systems including Electric Power Grid, Communications Grid, above Ground and Undersea Communication Lines, Oil and Gas Pipelines
  - Coronal Mass Ejection Pulse affects same items

High-Altitude Nuclear Explosion (HEMP)

- Area affected on Surface of Earth is “Line of Sight” of Nuclear Burst

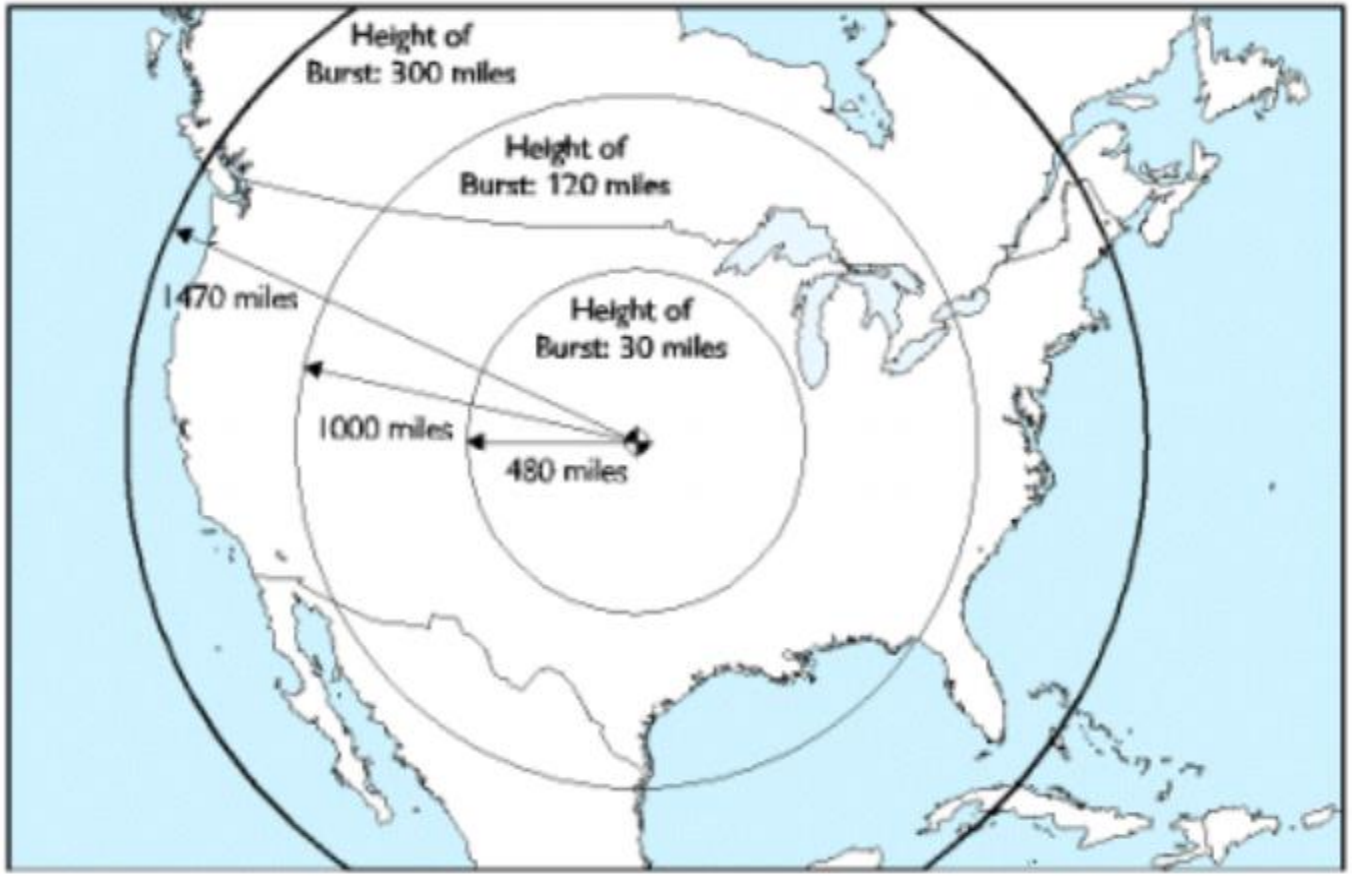


Figure 5: Area Effected by EMP by Height of Burst

Nuclear Generated EMP

HOB (Miles)	Affected Radius (Miles)	Effect	Delivery Methods	
300 Miles	1470 miles	1-5 MT Nuclear Explosion would give 50 kV/m at surface and 25 kV/m at 1470 miles	Low Earth Orbit (LEO), ICBM	Take out most electronics in USA and all of U.S. Power Grid for 1-2^{+} years
30 miles	480 miles	10 KT Nuclear Weapon could give 20 kV/m at surface	Ship launched SCUD off either coast, High Altitude Balloon, LEO	Could take out electronics from DC to NYC, and the Eastern Region of NERC (U.S. Power Grid)

Brief Summary of HEMP Effects

- E1 Pulse destroys electronics
  - SCADA's, PC's and Computers, components with short wires
    - Electronic system can be restored if spare parts available
    - Electric Grid has thousands of SCADA's and will go down hard
  - E1 can cause pinhole damage in insulation so motors, generators, transformers etc. fail later
- E3 Pulse induces High Voltages and Currents in Long Conductors
  - Can destroy most items plugged into the Grid
  - Can destroy Large Power Transformers (LPT's) in the Electric Grid
    - LPT's weigh up to 1 million lbs. and have a lead time of 15 months to 2 years in good times – Grid cannot be restored without their replacement
  - CME can do the same damage as an E3 Nuclear Pulse

Brief Summary of HEMP (continued)

- Observation
  - This is sure to be the Point of Focus for a Terrorist or Rogue Country wanting to collapse the US and our Economy
    - If entire Grid is down for 1+ years, up to 80% of population will perish in the process (per Congressional EMP Commission - ref. 2)
  - An EMP attack would be the first action taken by a major power wanting to invade the US Homeland

Introduction to Nuclear Weapons

- Fission Only – used in original Nuclear Weapons
  - Uranium-235 (U-235) or Plutonium-239 (P-239)
    - Must be compressed to “Critical Mass”
    - Fission process required neutrons to start and continue
  - Outputs lots of Gamma Rays (which cause the E1 Pulse)
  - Easy to build
  - Fission limited to 50 kT yield or less
  - 80-90% of development effort is to produce the U-235
  - U.S. produced Little Boy and Fat man in 4 years (from blank sheet of paper to deliverable weapon)

Introduction to Nuclear Weapons (con't)

- Fusion (Hydrogen or Thermonuclear Weapon)
  - Uses Heavy Hydrogen Isotopes (Deuterium and Tritium)
  - Tested up to 50 MT, thousands of warheads have been built in 1MT to 10MT range
  - Emits lots of Neutrons but few Gamma Rays
  - Must use Fission Bomb to start the Fusion process
  - Higher yield of Fusion gives larger E3 pulse
- Boosted Fission (midrange weapon)
  - Uses Fusion (with it's excess Neutrons) to accelerate Fission reaction
  - Enhances both E1 and E3

Who are the Nuclear Players?

Country	Date of First Test	Yield of First Test	Type of Explosion	Date of Other (Last?) Test	Yield of Test	Type of Explosion
USA	7/1945	18-20 kT	Fission			
USSR	9/1949	22 kT	Fission	10/1961	50,000 kT	Largest weapon Ever tested
UK	10/1952	25 kT	Fission	11/1957	1,800 kT	1st Staged Thermonuclear
France	2/1960	70 kT	Fission	8/1968	2,600 kT	1st Staged Thermonuclear
PR China	10/1964	22 kT	Fission	6/1967	3,300 kT	Staged Thermonuclear
India	5/1974	12 kT	Fission	5/1998	200 kT	Fusion/ Boosted
Pakistan	5/1998	40 kT	1stBoosted Fission	5/1998	20 kT	Boosted Fission
North Korea	10/2006	<1 kT	Plutonium Fission	9/2016	10 kT	Perhaps Super EMP

Nuclear Players continued

Country	Warheads Inventory (Active/Total)	
USA	1750/6970	
USSR	1790/7300	
UK	150/215	
France	290/300	
Israel	n.a./60-400	Probably 80
PR China	n.a./262	
India	n.a./110-120	
Pakistan	n.a./120-130	
No. Korea	n.a,/<10	

Nuclear Players (continued)

- Nuclear Weapons Worldwide
  - 1985 - 68,000
  - 2015 – 10,300 Total
    - 4,000 Active; 6,300 are stored or partially disassembled – none destroyed
- Israel
  - Development 1960-1979 – no test dates or yield info found
  - Number warheads likely 80
  - Yields unknown, likely Boosted Fission or Thermonuclear
- Pakistan
  - Unstable Government – Nuclear Weapons could fall into bad hands
  - Noted for selling nuclear weapons technology
    - Gas Centrifuge Technology to North Korea, Iran and Libya.
- North Korea
  - Has its own Nuclear Reactor to make P-239
  - Helped Syria build nuclear reactor in 2001 (Israel destroyed in 2007)
  - Helping Iran with Nuclear Reactor, Fission Nuclear Weapons & Missiles
- NATO Members – Belgium, Germany, Italy, Netherlands, Turkey
  - Host for approx. 200 U.S. Nuclear Weapons
    - Cannot arm without U.S. Authorization Codes

Most likely Scenario for Rogue State

- Rogue States likely limited to Fission (Iran is U-235)
  - Fission is easiest type to design and build
  - 80%-90% of effort is producing the Uranium-235
  - Use of U-235 in Gun Assembly is easiest and least development
    - USA dropped Little Boy without even testing it.
  - North Korea is higher tech and is making and using P-239 in Nukes
  - Yield for any Fission will be less than 50 kT
- Fission emits Gamma Rays - gives high E1 Pulse
  - Fusion would enhance E3 Pulse if they can do it
- My personal conclusion: Rogue States will not plan a single HEMP device over Kansas – no MT weapon and no Delivery
  - Most likely - 10-20 kT at 30 miles HOB over Baltimore and/or Portland with launch from a ship 200 miles off our coast

Some Thoughts

- Nuclear HEMP attack on the USA would likely go unanswered
  - Are we going to destroy a country that exploded a Nuke so high over our head that we only know what it was from the bright flash?
- There are plenty of Nukes out there for a Terrorist who has money
- Pakistan and North Korea will sell Nuclear Weapons or provide Nuclear Technology
  - China and Russia will sell Nuclear Technology and Parts for money
- Iran is intent on getting Nukes and will try to use them on the USA and Israel.
  - Have IRBM's (Shahab III) and continuing to develop/test Missiles (ICBM?)
  - Have successfully launched Shahab III from a ship in the Caspian Sea
  - Al Qaeda is reported to have 80 Ships around the world
- North Korea likely has Nukes based on P-239
  - May have been testing "Super EMP" and Boosted Fusion weapons
  - Have sold Intermediate Range Missiles – working on ICBM's
  - Have launched two satellites into Fractional LEO that fly near the USA
  - Are known to be trying to design a Missile capable warhead (using P239)

Effects of HEMP on Power Grid

- "The way our Power Grid is partitioned, a 10 kT burst at 30 km (20 miles) over the Eastern NERC Interconnection would cause blackout for approx. 75% of the Country and the most populated portions of Canada" [(4)]
- Within a year after a Natural or Nuclear EMP Catastrophe, approx. 2/3 of U.S population – 200 million Americans, would likely perish from Starvation, Disease and Societal Collapse[(2)]

Metatech Simulation Effects of E3 HEMP Pulse on Power Grid (12)

- Computer Model developed under contract to FERC and Oakridge National Laboratory
  - U.S. Electric Grid Transmission network was modeled
- Transmission network is most impacted by HEMP E3
  - Due to Large Power Transformers in system
- Conductivity of Earth (to a depth of 300 km) was important
  - Determines the magnitude of **Geometrically Induced Current (GIC**)
  - The flow of GIC in Transformers is root cause of all power system problems resulting from E3 HEMP (or Solar Storms).
- E3 HEMP pulse is two different physical parts:
  - E3A – Blast Wave portion (1 – 10 seconds)
  - E3B – Magnetic Field Heave portion (10 – 300 seconds)

U.S. Power Grid HV Transmission Lines

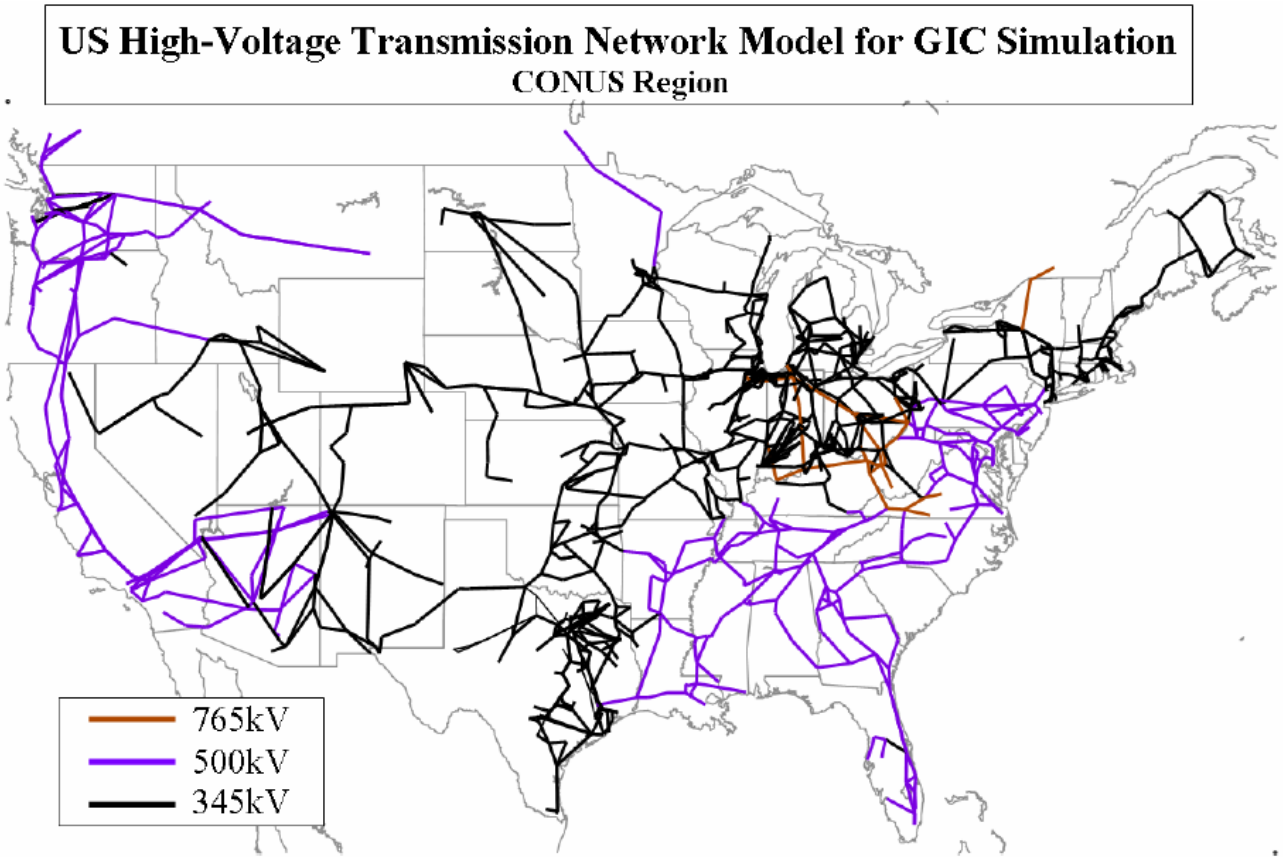


Figure 2-25. Map of 345kV, 500kV and 765kV substations and transmission network in U.S. grid model.

Metatech Simulation Cases

- Congressional EMP Commission requested several cases to quantity the effects of E3 HEMP on the U.S. Power Grid[12]
  - In Metatech report[12], the Nuclear Device is only described as a “high yield device”.
  - HOB for E3A cases – 500 km; E3B cases 170 km
  - “Area” of circles is proportional to the GIC current flow
    - Green color indicates flow of GIC into ground
    - Red color indicates flow of GIC out of ground
  - Outlined regions would experience total collapse of Grid
    - Areas outside could experience cascading outages
- Remember that the E1 EMP Pulse has already occurred and done its damage to Electronic Systems and Computers

E3B over Portland and Ohio

HOB = 170 km

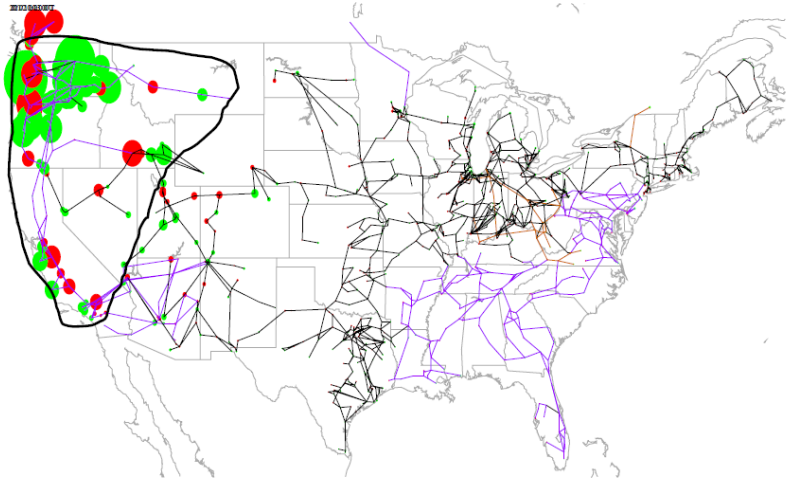


Figure 3-8. Summary of GIC flows in U.S. power grid for E3B from burst centered on Portland, Oregon.

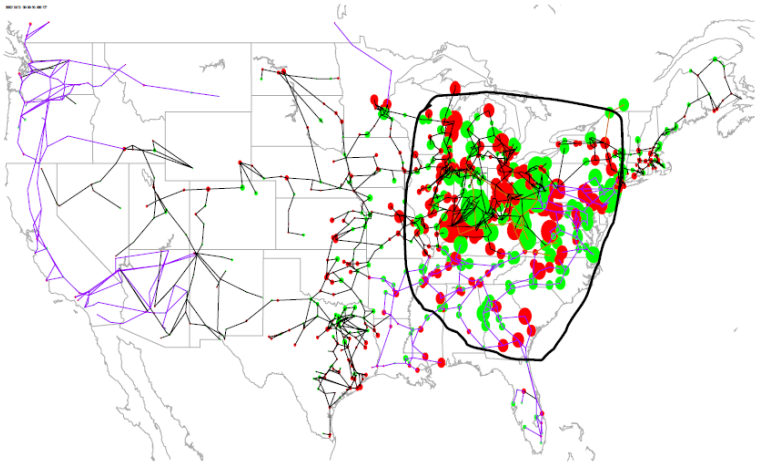


Figure 3-5. Summary of GIC flows in U.S. power grid for E3B from burst centered on the Indiana, Ohio and Kentucky border.

E3A over Portland (L) and Chicago(R)

HOB = 500 km

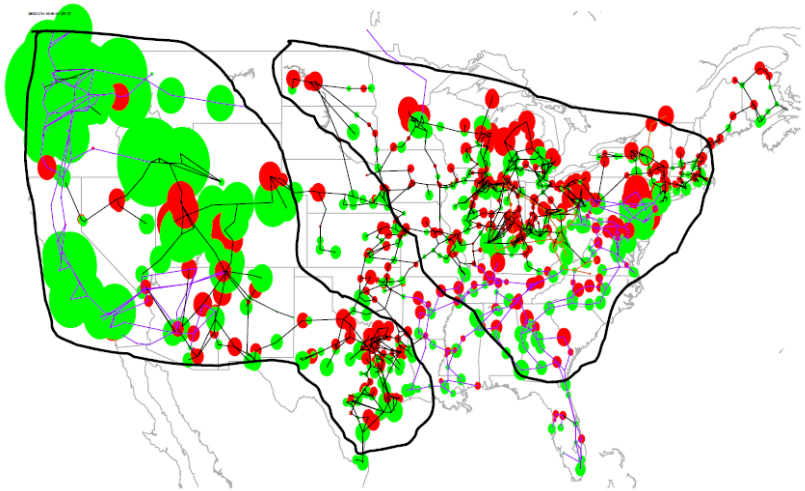


Figure 3-14. Summary of GIC flows in U.S. power grid for E3A Blast Wave Case B15a.

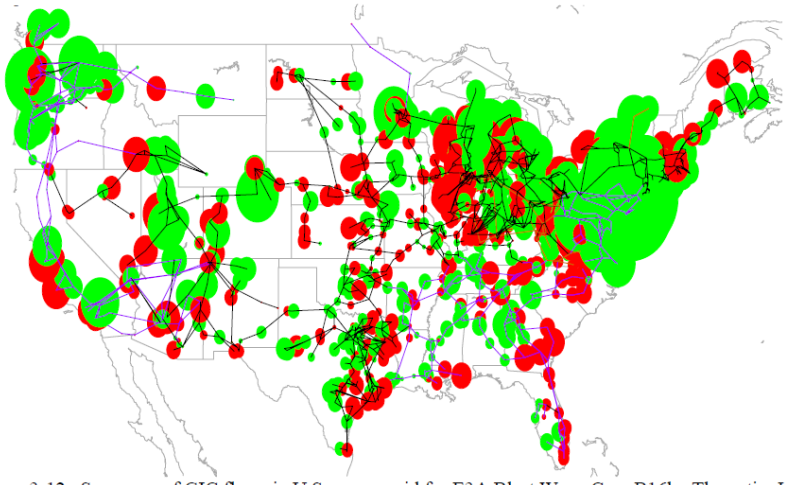
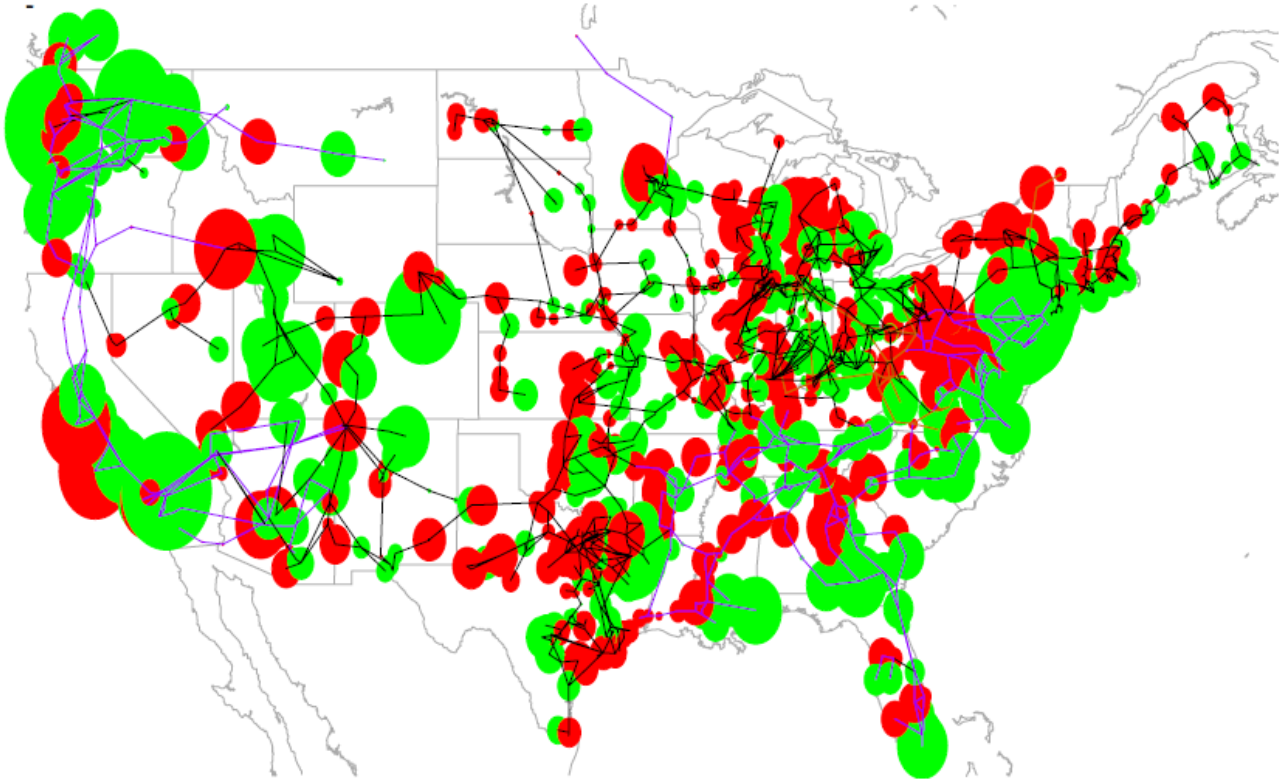


Figure 3-12. Summary of GIC flows in U.S. power grid for E3A Blast Wave Case B16b. The entire U.S. Power Grid is expected to collapse.

E3A over and NYC

HOB = 500 km



igure 3-13. Summary of GIC flows in U.S. power grid for E3A Blast Wave Case B17a. The entire U.S. Power Grid is expected to collapse.

Effects of HEMP on Automobiles

- Congressional EMP Commission tested cars and trucks at L-3 facility in Colorado [2] [21]
  - Tested 37 cars (1986 – 2002) up to 50 kV/m
  - Tested with cars running and not running
  - 3 cars stopped at 30 kV/m but could be restarted
  - 25 had minor malfunctions (dashboard lights etc.)
  - 8 did not exhibit any anomalies
  - Cars were borrowed so testing did not continue to 50 kV/m if an anomaly occurred at lower level

Effects of HEMP on Trucks

- Tested 18 trucks (1991 – 2003) up to 50 kV/m
  - Trucks ranged from gas powered pickups to large diesel powered tractors
  - Of the Trucks tested while not running, none were affected
  - 13 exhibited a response while running
    - 3 of the motors stopped
    - 2 of the three could be restarted, the third had to be towed
    - 10 developed minor responses
    - 5 had no negative response at all
  - Trucks were borrowed so testing was stopped when any anomaly occurred – did not continue to 50 kV/m

EMP Effects on Autos and Trucks Conclusion

- Stopping testing at first anomaly may have made results optimistic
- Since Model Year 2002/2003
  - The reliance on microprocessors in all motor vehicles has increased greatly.
  - The sensitivity and speed of computers and electronic circuitry as increased
  - Testing of newer cars and trucks is needed
- Auto manufacturers have performed EMP testing on vehicles at White Sands
  - Test results and models of cars tested has been kept secret – cars were covered at all times to hide identity

Effects of Long Term Electrical Outage

- Telecommunications
  - Loss of telecommunication impacts every infrastructure
- Banking and Finance
  - Almost all money is electronic
  - Almost all transactions are performed electronically
  - Where is your money and how would you get it?
- Fuel/Energy Infrastructure
  - Process control (SCADAS's) is electronic for pipelines, refineries, distribution
- Transportation Infrastructure
  - No fuel, telecom, street lights -----

Effects of Long Term Electrical Outage-continued

- Food Infrastructure
  - 2% of population feeds 98% + exports
  - Food available for 1-3 days – Supermarket; up to 1 month from Warehouses
  - Distribution depends on Transportation
- Water Supply Infrastructure
  - Drinking Water, Water Treatment and Sewage Treatment depend on Electric Power (pumps, SCADA etc.)
  - 75,000 Dams, 168,000 Water Treatment Plants, 19,500 Wastewater Treatment Plants
- Emergency Services
  - Police, Fire, Rescue, Medical communications shut down
    - Will they even show up for work – won't get paid, have to survive themselves
- Space Systems
  - Satellites in LEO will fail from collateral radiation cloud in space

Effects of Long Term Electrical Outage-continued

- Government
  - If no Government or if Government cannot function or communicate:
    - No Police, Fire, FEMA, Food Lines – no help from Gov't
    - Rule of Law will break down into chaos (societal collapse)
    - Looting and Riots
  - Can't keep Citizens informed
    - Who is the "Law" if citizens don't know status of Gov't
    - HAM radios are the only way we will have a chance to find out what is going on

Solar Storms

GEOMAGNETIC STORMS

- Geomagnetic Storms
  - Geomagnetic Disturbance (GMD) is created when the Earth's Magnetic Field captures Ionized Particles from a Coronal Mass Ejection from the Sun
  - Coronal Mass Ejection (CME)
    - Ejection of charged particles (Plasma) from an Explosion on Sun
    - Takes 1-2 days to travel to Earth
    - CME cloud can be very large in size compared to the size of the Earth
      - Sun diameter = 864,938 miles, Earth = 7,918 miles (110 X)
  - GMD's generate E3 pulse similar to HEMP E3
    - No E1 or E2 pulse – no effect on autos, PC's etc. except through Power Grid
    - E3 from GMD can linger for hours – even days

Coronal Mass Ejection - Image from SOHO Spacecraft

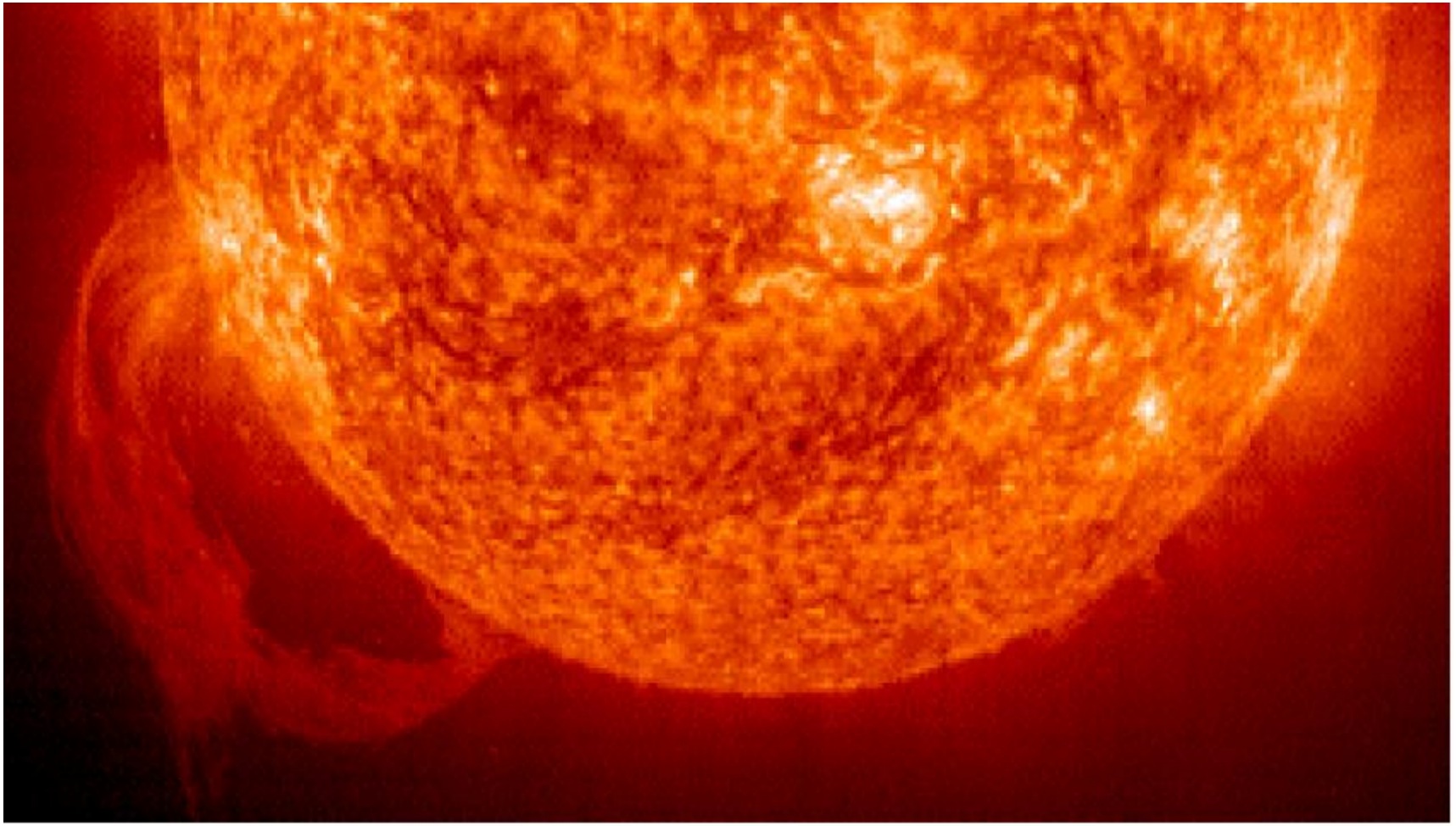


Figure 3-1. SOHO image, June 9, 2002.

Solar Storm Information

- Solar Flares – giant bursts of energy & X-Rays
  - Do not affect Grid or cause major damage on Earth
- CME Field measured in nT/min (nanoTeslas/min)
- Magnetic field varies slowly
  - Rise time is as fast as a few seconds
  - Pulse Width is up to an hour
- Geostorms can happen at any time
  - Pose a near “continuous probability”
- Power Grid has gotten much more complex and fragile
  - 1950’s – 115 kV to 230 kV Transmission
  - Present – 345 kV, 500kV and 765kV across Continent

Data on Some Past Solar Storms

- 1859 (Aug. & Sept.) – Carrington Event
  - Telegraph wires ignited and started Forest Fires, started fires in Telegraph Stations
  - Destroyed first Trans Atlantic Telegraph Cable
  - Considered to be the Standard for a 100 Year Storm
- 1921 (5/14 – 5/15) – Railroad Storm
  - 4800 nT/min
- 1982 (7/13 – 7/14) – Sweden System Collapse (20)
  - 2500 nT/min
- 1989 (3/13 -3/14) – Quebec System Collapse
  - 500 nT/min
- 1992 (5/10/92)
  - 350 nT/min

Quebec Storm

- Quebec Storm
  - 500 nT/min
  - Collapsed the entire Hydro-Quebec Power Grid in 92 seconds
  - 6 million people lost power for nine hours
  - Nearly brought down the US Eastern Interconnect regions in a cascading collapse
  - Several LPT's damaged including one at a Nuclear Power Plant
  - Lots of data available on this failure so is used for checking simulation models[10] and scenarios

Prediction of Effects from Future Large Solar Storms

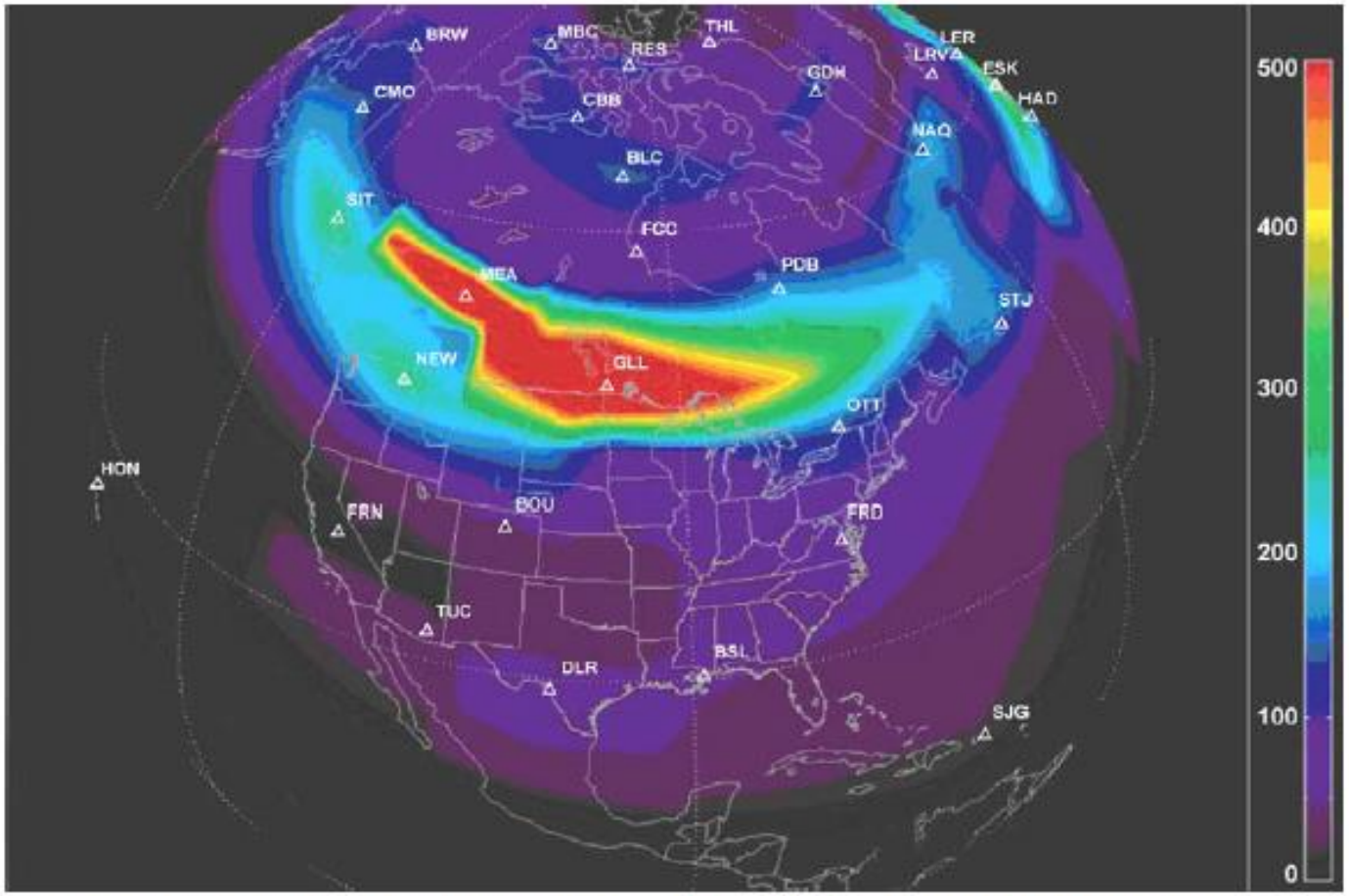
Metatech Simulation Effects of Geomagnetic Storms on Power Grid[(10)]

- Computer Model developed Metatech[(10)] under contract to FERC and Oakridge National Laboratory
  - U.S. Electric Grid Transmission network was modeled
  - Transmission network is most affected by CME Solar Storm
- Model verified by running 1989 (Quebec) and 1982 (Sweden) Solar Storms
  - 1982 Storm is rotated 120^{o} Latitude and 5^{o} Long to show it's effects as if it occurred over Canada and US
- Model used to develop scenarios for 1859 Carrington Event (1 in 100 Year Storm events)

FERC and Oakridge (Metatech) Study[10] Conclusions

- 1989 Quebec system collapsed at impulse of 400 nT/min
  - Conclude 400 nT/min is threshold value for major LPT damage
- Based on 1859, 1921, 1982 and other major storms, conclude:
  - Expect Storm of 1989 Quebec magnitude every 30-50 years
  - Expect Storm of 5,000 nT/min magnitude (1921 or worse) every 100 years

Simulation of Quebec Collapse

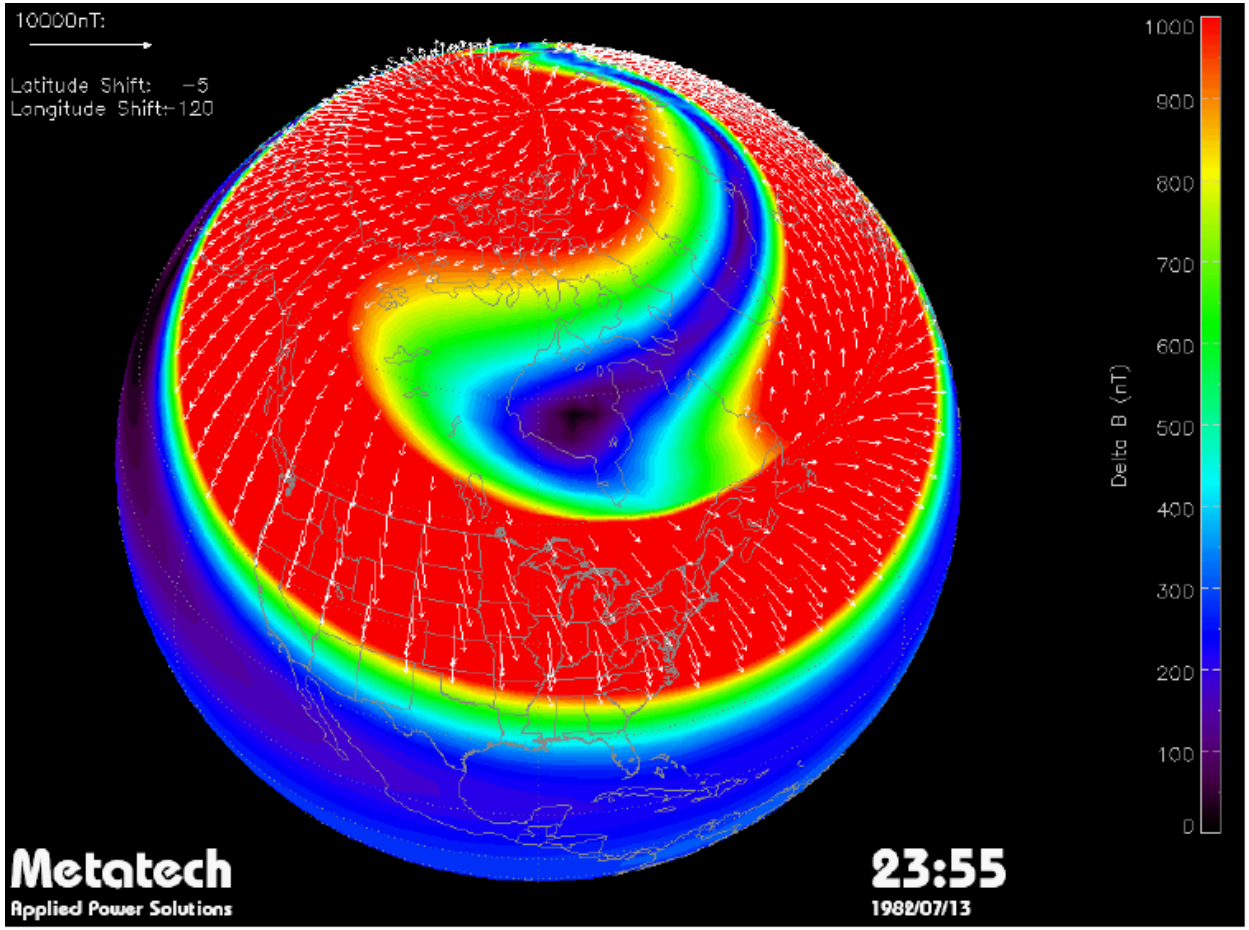


Geomagnetic field disturbance conditions, dB/dt (nT/min) over North America at time 7:45 UT on March 13, 1989

Source: Metatech Corporation, Applied Power Solutions

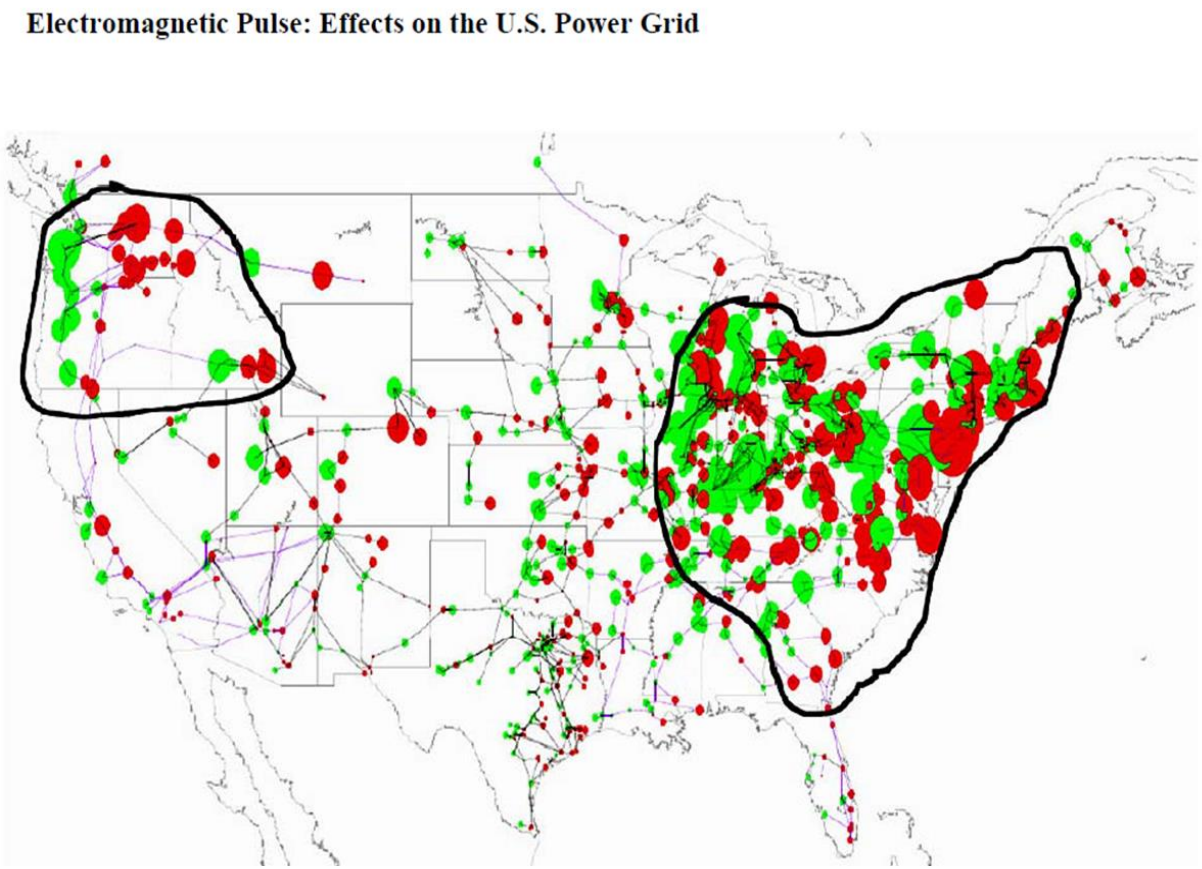
Figure 5. Extent of 1989 Geomagnetic Storm

Simulation of 1982 Sweden Storm Rotated to place it over US



re 3-13. Geomagnetic field disturbances rotated by 120° longitude and stretched southw
by 5° latitude over North America, July 14, 1982 at 23:55 UT.

FERC Executive Summary



- Shows areas affected in a 4800 nT/min Pulse (Railroad Storm or E3 Pulse) at Latitude of 50 degrees N.
- Outlined area shows areas of probable system collapse
- Reference 9 & 10

Impact of Solar Storm on Electric Grid

- 100 Year Solar Storm centered over Southern Canada – per Metatech FERC Study (8)
  - 365 EHV Transformers fail
  - Power collapse in North East, Mid Atlantic, Pacific Northwest affects 130 million (40% of population)
  - Power outage lasts 4-10 years
- If 100 Year Storm centered over northern region of U.S.
  - Blackout extends through Southern Calif, Florida and parts of Texas

100 Year Solar Storm Scenario (10)

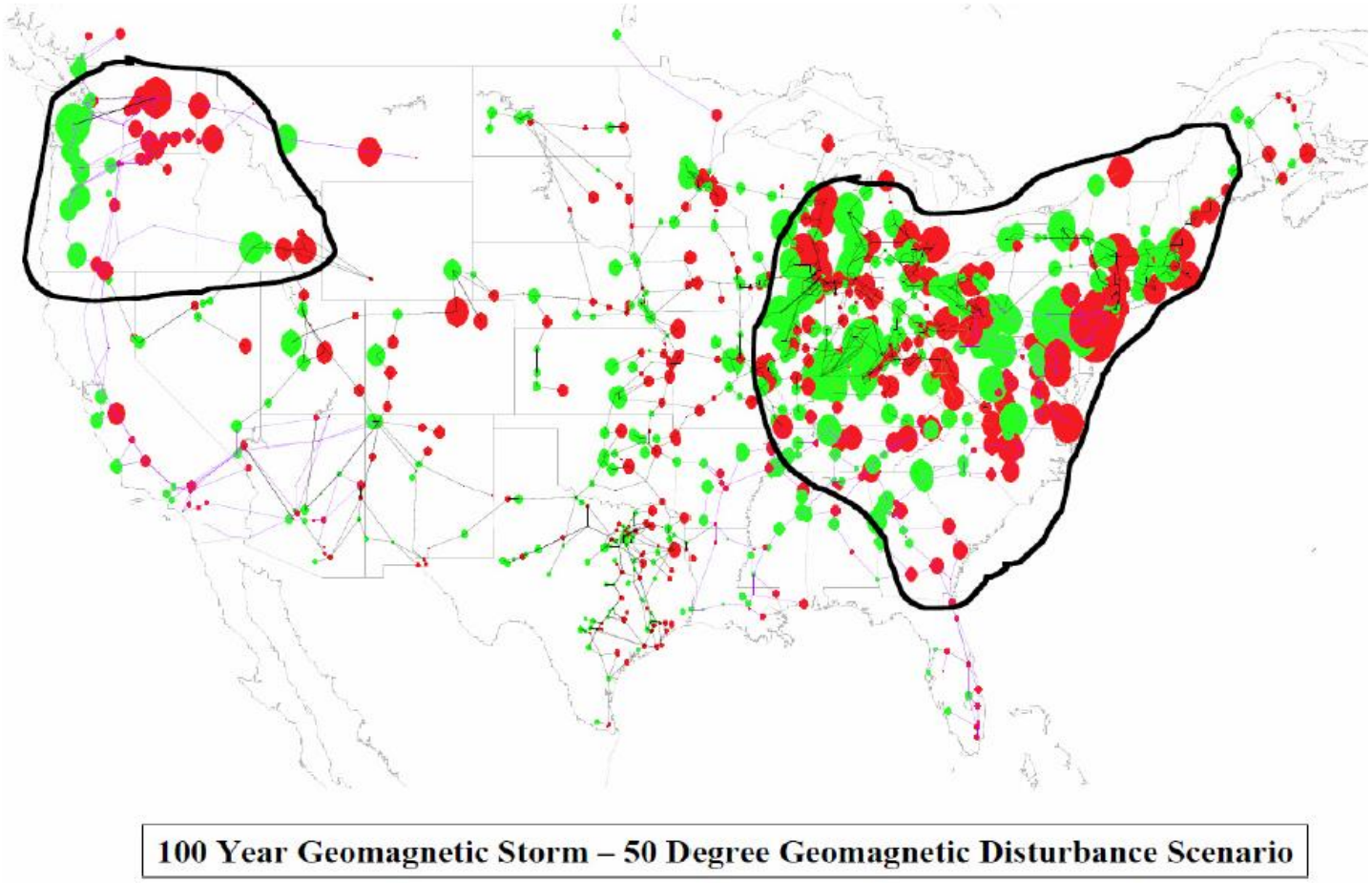


Figure 3-25. 100 Year geomagnetic storm – 50 degree geomagnetic disturbance scenario. The above regions outlined are susceptible to system collapse due to the effects of the GIC disturbance.

100 Year Solar Storm Scenario (10)

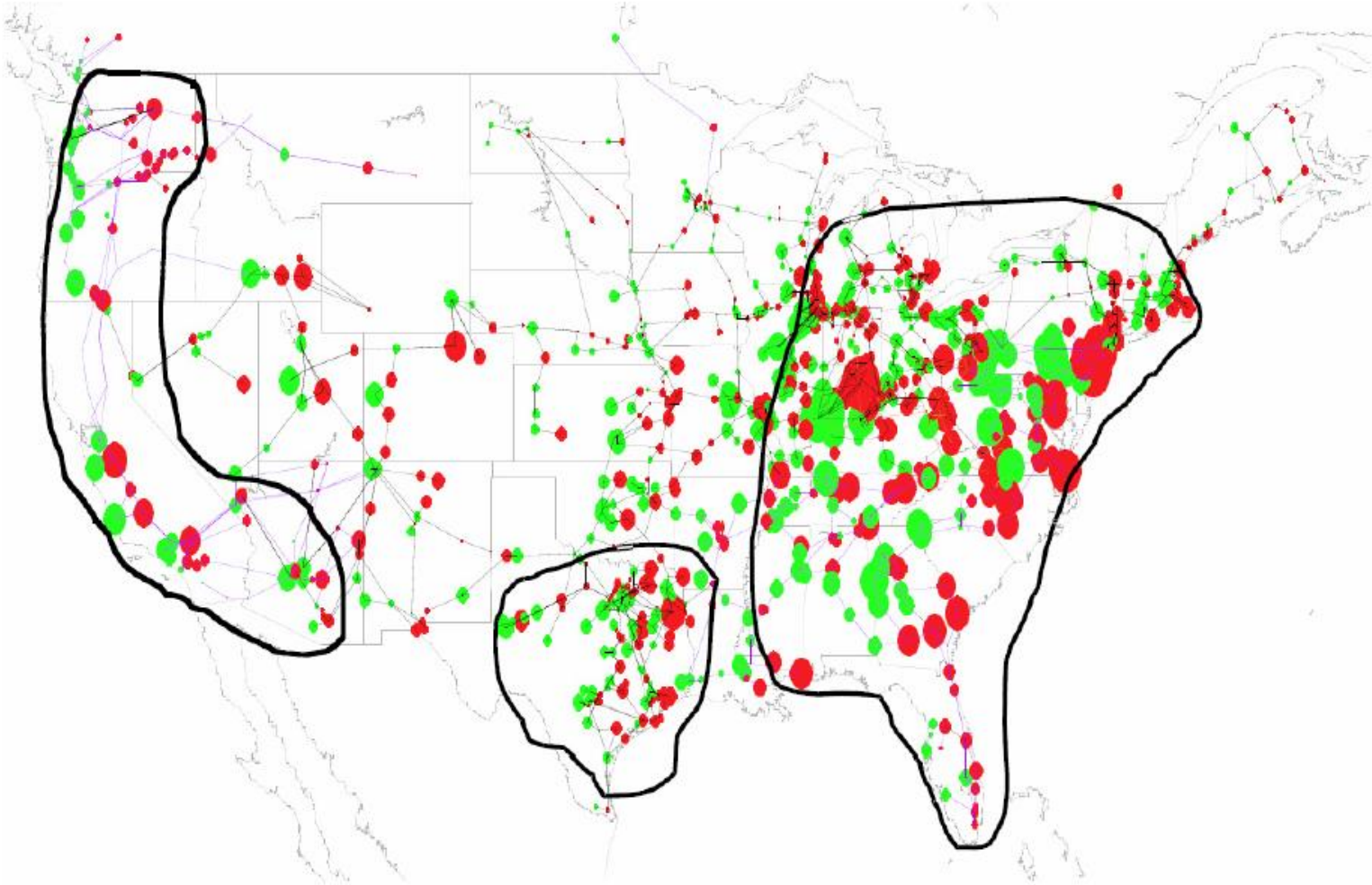


Figure 3-26. 100 Year geomagnetic storm – 45 degree geomagnetic disturbance scenario. The above regions outlined are susceptible to system collapse due to the effects of the GIC disturbance.

Intentional Electromagnetic Interference (IEMI)

- IEMI Definition
  - Non Explosive, non Nuclear intentional malicious generation of intense Electromagnetic fields for the specific purpose of disrupting, confusing or damaging electronics for **Terrorist or Criminal** purposes[14]
    - New IEC category of Terrorist – "Electromagnetic Terrorist"
    - IEMI does not include hacking or cyberwar
- FERC Report
  - Entire Power Grid can be blacked out for weeks or months by knocking out only 9 of the Country's Electric Transmission Substations [22]
- Range is 100's of meters

Intentional Electromagnetic Interference (IEMI)

- Military – Lots of Activity in HPM
  - Critical U.S. Military Systems are hardened to EMP
  - USS David Cook Incident – on 4/14/2014, the onboard Aegis Combat System was completely disabled by a low overfly of a Russian SU-24 in the Black Sea -
  - U.S. has released some information on HPM Programs
    - CHAMP (Boeing) – May 2012 a HPM system on a Cruise Missile (from B-52) flew over 7 separate targets and disabled (not jammed) them over the period of 1 hour[24]
  - There is a lot of HPM (IEMI) technology being implemented on the military side
    - Provides an insight to what can be done using IEMI.

Metatech Report on IEMI[(14)]

- Several IEMI devices are commercially available
- IEMI is similar to E1 EMP Pulse
- Can be Narrowband or Wideband
  - Frequencies for IEMI generally 300 MHz to 5 GHz
  - It is easy to deliver Narrowband at thousands of Volts/m
- Electric Power Grid Devices Vulnerable to IEMI
  - Computers of all kinds
  - SCADA systems, including PLC's, DCU's
  - Communication devices
  - Solid State Safety Relays
- Hierarchy of System vulnerability in Power Grid
  - High Voltage Substation Controls and Communications
  - Power Generation Facilities
  - Power Control Centers
  - Distribution Transformers
  - Distribution Line Insulators

Concept for IEMI Delivery

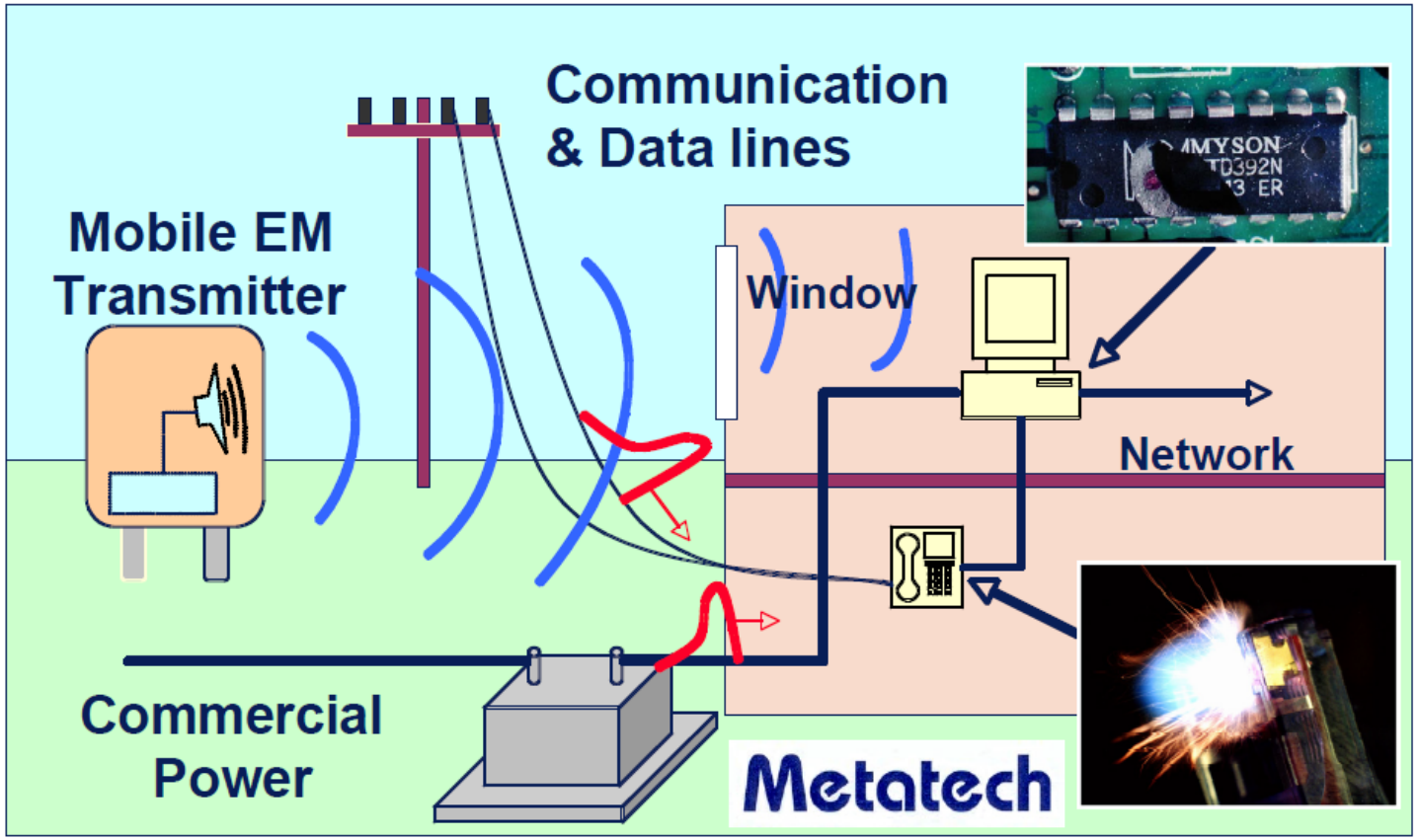


Figure 2-5. Typical IEMI interactions of radiated fields.

Commercially available IEMI Generator

- Diehl Munitions Systeme is marketing 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

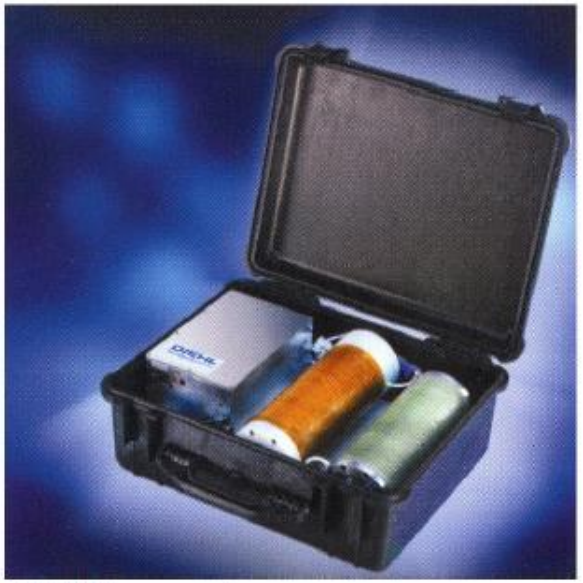
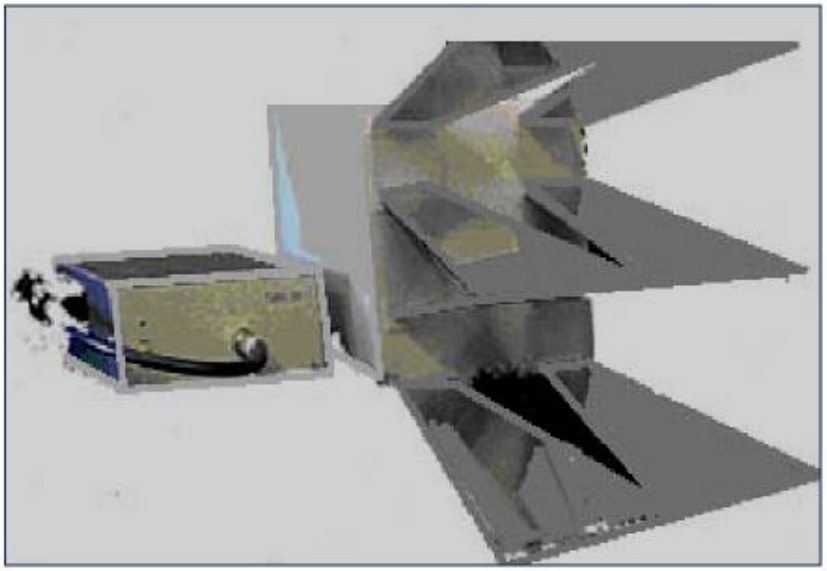


Figure 2-6. DIEHL Munitions damped sine IEMI generator.

Plans are online to make this Device



Parameters	Values
Amplitude at 20 m distance	2 kV/m
Pulse duration	0.2 ns
Pulse repetition rate	Up to 1000 Hz
Antenna aperture	0.35 m x 0.35 m

Source: Dr. Yuri Parfenov, Russia

Figure 2-7. Laboratory hyperband pulse generator used in Russia.

Example of High Power IEMI Device

AFRL has developed an extremely powerful IRA system that produces UWB pulses

- –E*R = 5.3 MV
- –pulse width ~100 ps

Figure 2-9. High intensity JOLT hyperband generator used in the United States.

U.S. Power Grid

U.S. Power Grid

- U.S. Power Grid is Backbone to U.S. Economy and our Standard of Living – is our most Critical Infrastructure
- U.S. Electric Power Grid is “Brittle” and “Binary” and it fails “Fast and Hard” – Prof. Geo Baker in testimony before Congress
- The Longer the Grid is “Down”, the Harder is the “Recovery”
- Transmission Lines are tightly interconnected
- “Enormously complex system of systems”
- Instantaneous unanticipated loss of Load can cause System Collapse – a possibility at 1%, a certainty at 10%[(2)]
  - Large scale load losses in excess of 10% are likely at EMP threat levels[(2)]

Power Grid continued

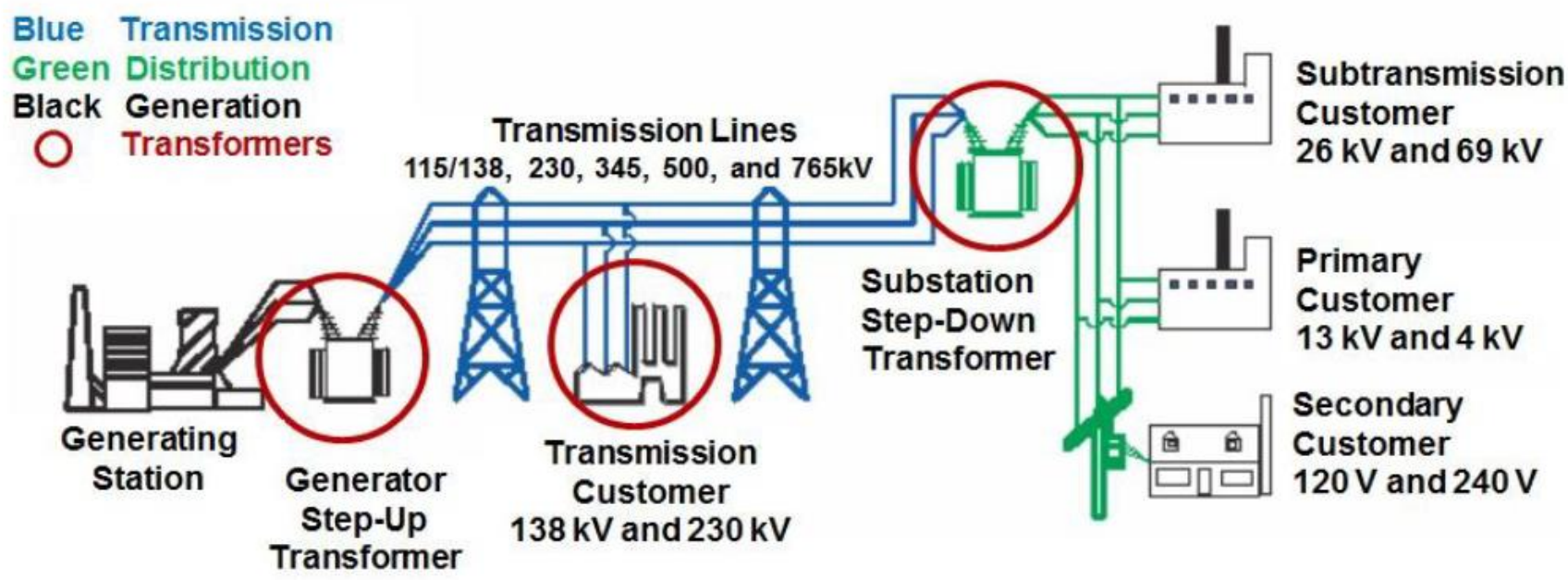
- Number of Large Power Transformers (LPT's) damaged is the key to how long the Grid will be "Down"
  - There are 2,146 LPT's in the Power Grid
  - 15 month lead time in good times per EMP Commission
  - Worldwide production of LPT's is 100/year (2008)
  - Design life is 40 years, average age of LPT's in the U.S. is 42 years, some are 70 years old

U.S. Electric Grid Components

- Power Generation
  - 16,472 - Number of Power Generation Plants over 1MW
  - 104 Nuclear Plants in US – mostly east of Mississippi
    - Generate 20% of all Electricity generated in U.S.
- Transmission Lines (High Voltage)
  - 155,000 Miles of High Voltage Transmission Line
    - 45,600 miles – 345 kV
    - 23,800 miles – 500 kV
    - 2,100 miles – 765 kV
  - Number of EHV LPT's (Large Power Transformers)
    - 1,501 – 345 kV
    - 587 - 500 kV
    - 58 - 765 kV
- Distribution
  - Low voltage lines and transformers

U.S. Electric Grid Representation

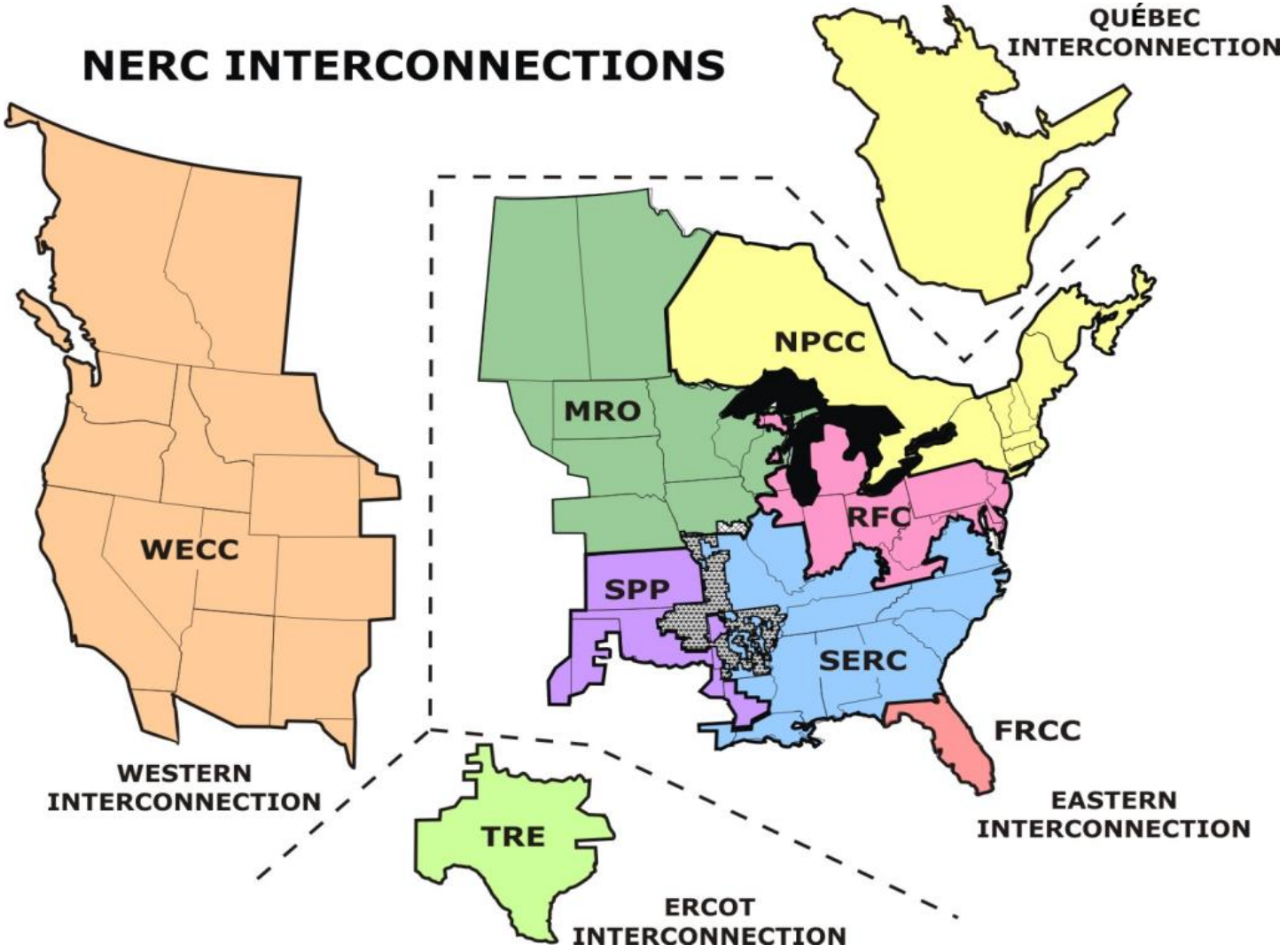
Figure 1. Electric Power Grid Representation



Source: DOE, 2006; see Footnote 14. Modified based on industry review.

FERC and NERC Management

- FERC – Federal Energy Regulatory Commission
  - 5 members (Commissioners)
  - Legal Regulator of NERC
- NERC – North American Electric Reliability Corporation
  - Private Corporation
  - Members represent Power Generation and Transmission Owners
- U.S. Electrical Grid
  - 3 Main Electrical Grids (Interconnections) in U.S.
    - Eastern Interconnection – serves 70% of Population and Electrical Load
    - Western Interconnection
    - Electric Reliability Council of Texas (ERCOT) Interconnection
  - 8 Regional Entities are part of 3 Main Grids


NERC INTERCONNECTIONS
QUÉBEC INTERCONNECTION
NPCC
MRO
RFC
SPP
SERC
FRCC
WECC
TRE
WESTERN INTERCONNECTION
EASTERN INTERCONNECTION
ERCOT INTERCONNECTION

Example of EHV Transformer

Figure 4. Transport of Large Power Transformers

Note: Workers move wires, lights, and poles to transport a 340-ton power transformer, causing hours of traffic delay.

Source: Pittsburgh Live News, December 2011.

Example of EHV Transformer

- Large Transformers >1,000,000# Assembled and Oil Filled
- Special Trailers - ~300 Feet, >19 Axles, 6 People to Drive
- Oil Draining, Disassembly Before Moving Oil Filling and Assembly After Moving
- Dedicated Team of Skilled People for Each Transformer – Several Weeks duration typical

Damaged EHV from Quebec Collapse

Figure 2-33. Damaged transformer at the Salem Nuclear Plant.

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This is a short introduction to “How Nuclear Weapons Work”. This was not part of the 1/10/2017 Presentation but I added it onto the end before I sent it out to Michael for distribution to anyone interested.

Introduction to Nuclear Weapons

- Energy Mechanism
  - Fission
    - Uranium 235 or Plutonium 239
    - Provides lots of Gamma Rays which generates E1 EMP
    - All Fission Reactions are started with High Explosives (unless classified methods exist)
    - Fission Weapons have about 50 kT yield as an upper limit
  - Boosted Fission
    - Uses Deuterium and Tritium Fusion to Boost the Fission reaction
  - Fusion
    - Uses Deuterium and Tritium for Fusion
    - Fission is still used to start the Fusion Reaction
- Use USA WWII Nuclear Weapon Development as example
  - Developed and produced 2 weapons – go-ahead to delivery in 4 years
  - Fission Only
  - Little Boy and Fat Man Delivered

Nuclear Fission Reactions Used in Weapons

- (U-235 used in Little Boy – dropped on Hiroshima)
- U-235 comes from mined U-238 (0.7% is U-235). Separated (enriched) by:
  - Gaseous Diffusion Centrifuges
  - 20% enrichment is “highly enriched”
  - 90% enrichment is “weapons grade”
- $U^{235} + n \rightarrow Sr^{95} + Xe^{129} + 2n + 180\ MeV$
  - 7% of 180 MeV energy of reaction is Gamma Rays which generates E1 pulse
  - Must compress U235 explosively to achieve “Critical Mass”, then shower with Neutrons from Neutron Generator
  - Must hold “Critical Mass” as long as possible because Fission stops when Critical Mass is lost

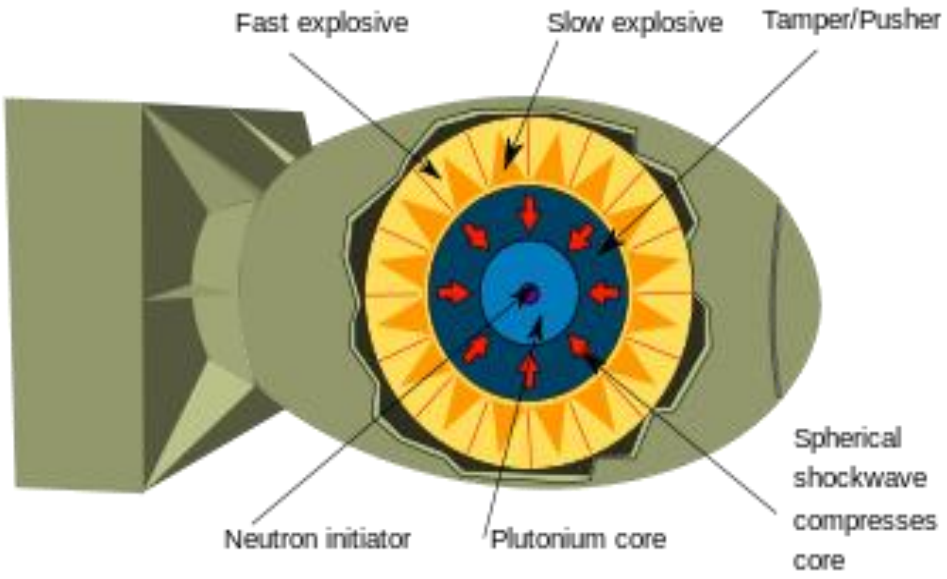
Fission (continued)

- (P-239 used in Fat Man - dropped on Nagasaki)
- P-239 made by placing U-238 in a Nuclear Reactor
  - P-239 separated chemically after removal from Reactor
  - 90% enrichment is Weapons Grade
- $P^{239} + n \rightarrow Xe^{134} + Zr^{103} + 3n + 207MeV$
  - 15% of 207 MeV energy of reaction is Gamma Rays which generates E1 pulse
  - Same requirement to explosively compress to Critical Mass and hold together for as long as possible during Fission Reaction

Little Boy

- Gun Assembly Concept
  - Two “subcritical” masses of U-235 placed at either end of a closed end cylinder.
  - High Explosive placed behind one mass sends it down tube - slams into mass at other end of tube to achieve Critical Mass
  - Mass is simultaneously showered with Neutrons from Neutron Generator to start Fission
- 141 lb of 80% enriched Uranium
  - This was the total of all U-235 produced by Oakridge
  - Bomb was dropped on Hiroshima without ever testing concept
  - Only 1% (1.12 lb.) of U-235 Fissioned before Critical Mass was lost
  - Bomb Weight = 9,700 lb., Length – 10 ft., Diameter = 28”
- Yield = 15 kiloton
- 80 – 90% of Manhattan Project effort for Little Boy went into making and processing the U-235

Fat Man



- Implosion Concept
  - Plutonium surrounded by 5,300 lb. of High Explosive
  - Bomb Weight = 10,800 lb.
  - Length = 10’ 8”, Dia. = 60”
  - 13.6 lb. of 90% enriched Plutonium
  - 20% of P-239 Fissioned before Critical Mass was lost
  - Yield was 21 kiloton
  - Concept more efficient but more complex

Boosted Fission and Fusion

- Fusion (Hydrogen or Thermonuclear Bomb)
  - Produces lots of Neutrons but no Gamma Rays
  - Uses Deuterium and Tritium (Hydrogen with Extra Neutrons)
  - All Fusion Reactions are started using Fission
  - Fusion weapons up to 50 MT have been tested
  - All USA Bombs and Warheads now use Thermonuclear to get small size and high yield
    - Megaton class warheads are 18” diameter and weigh 720 lb.
- Boosted Fusion
  - Uses fast Neutrons escaping the Fusion process to enhance/accelerate the Fission process by adding extra Neutrons
    - Increases yield by causing more Fissions before lose Critical Mass