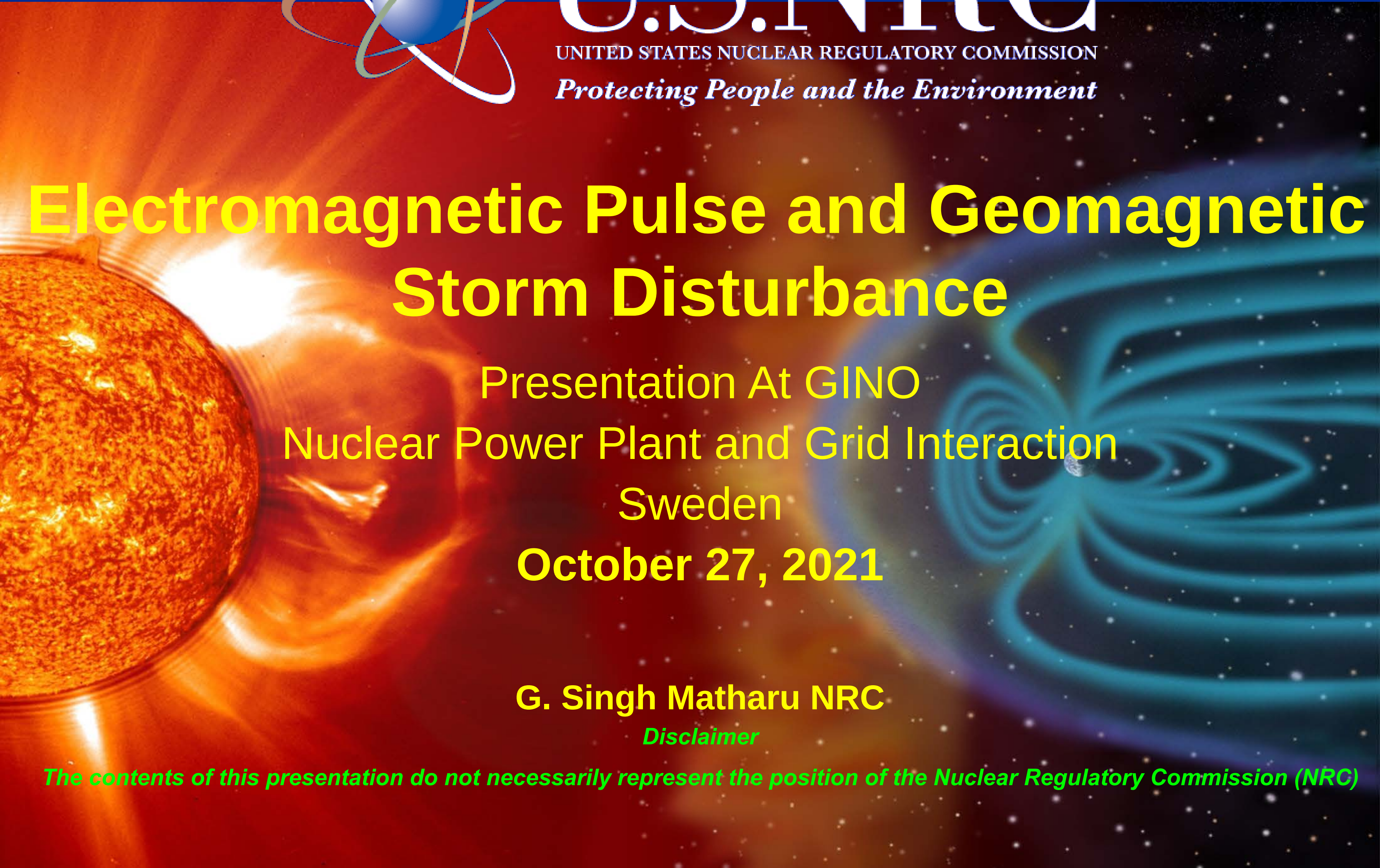
U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

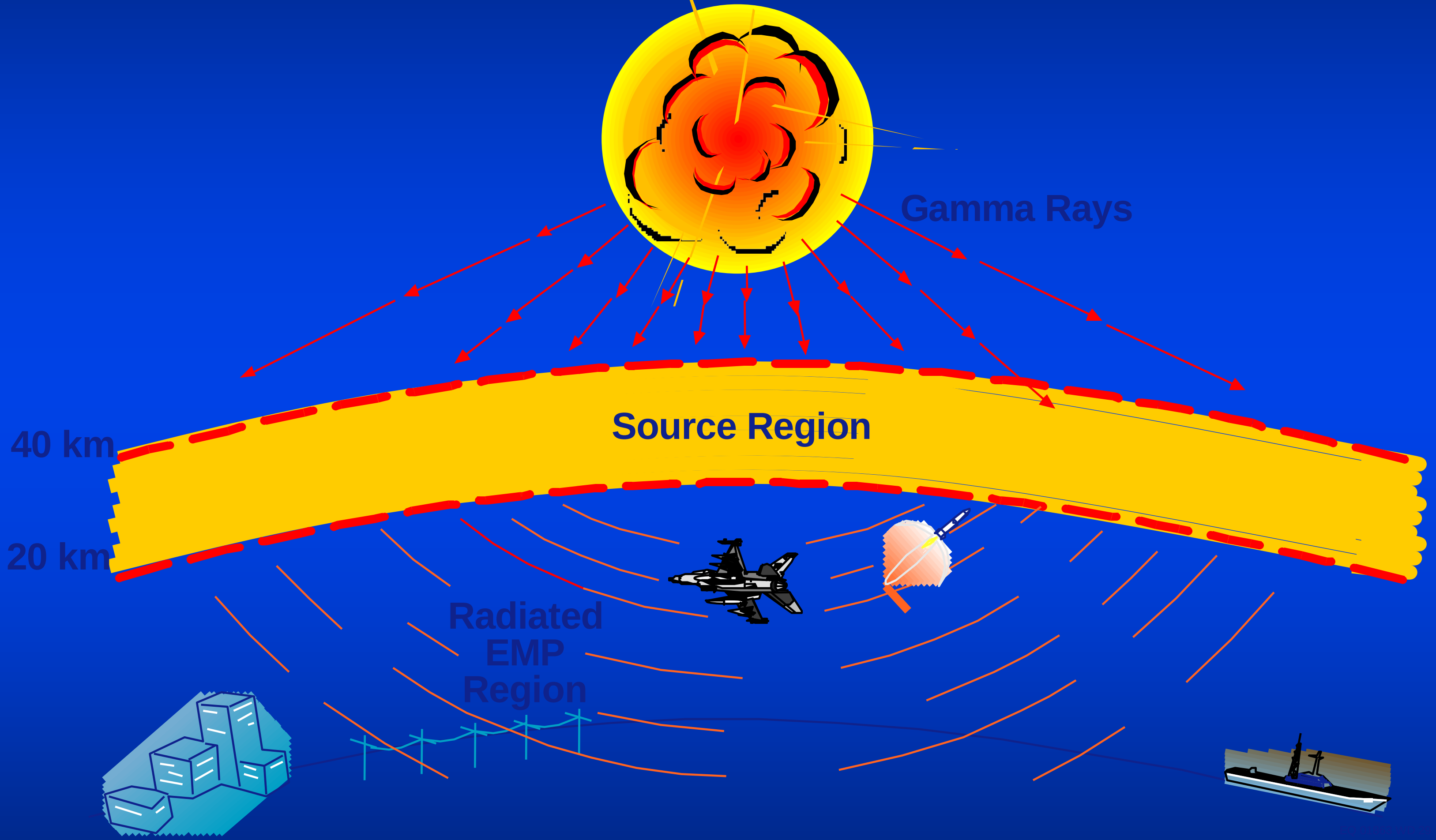


Electromagnetic Pulse and Geomagnetic Storm Disturbance

Presentation At GINO
Nuclear Power Plant and Grid Interaction
Sweden
October 27, 2021

G. Singh Matharu NRC

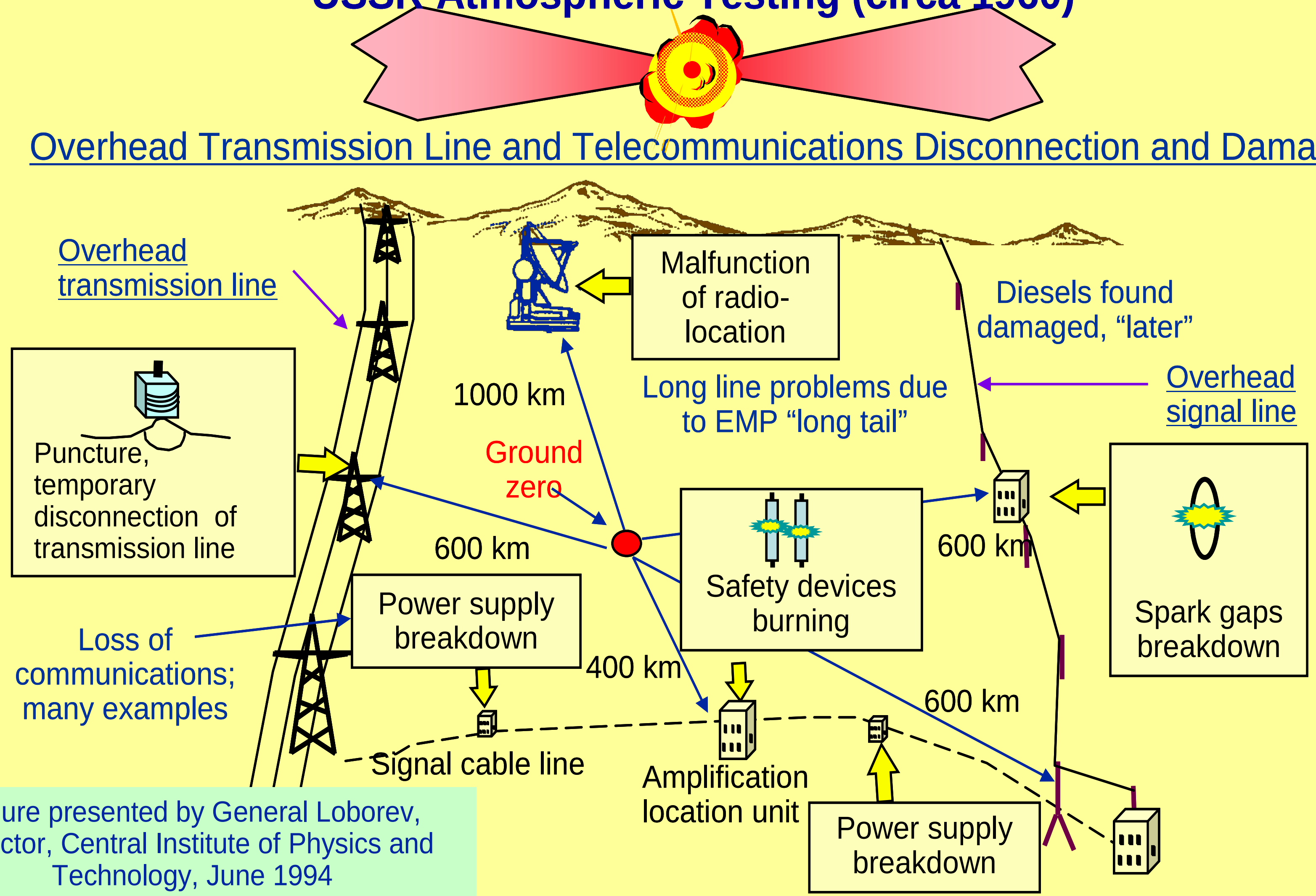
High-Altitude EMP produced by detonations above source region



Can expose all systems within line of sight

Soviet Union HEMP test over Kazakhstan

Observed EMP Anomalies During USSR Atmospheric Testing (circa 1960)



Overhead Transmission Line and Telecommunications Disconnection and Damage

Overhead transmission line

Puncture, temporary disconnection of transmission line

Loss of communications; many examples

Malfunction of radio-location

1000 km

Ground zero

Long line problems due to EMP "long tail"

Diesels found damaged, "later"

Overhead signal line

600 km

Power supply breakdown

Safety devices burning

600 km

Spark gaps breakdown

400 km

600 km

Signal cable line

Amplification location unit

Power supply breakdown

Figure presented by General Loborev, Director, Central Institute of Physics and Technology, June 1994

Starfish Prime test

- Starfish Prime, 9 July 1962, 1.4 Mt, 400 km above Johnston Island
- Effects measured on varied systems over a wide area of the Pacific
  - Transmitters
  - Military radio
  - Street lights
  - Undersea cables
- Consistent with Soviet experience during K184 test with damage and disruption effects on power and telecommunications networks
- Modern electronic technologies are significantly more vulnerable than analog devices were 60 years ago

Starfish fireball seen In Honolulu 800 miles away

Nuclear HEMP Tests

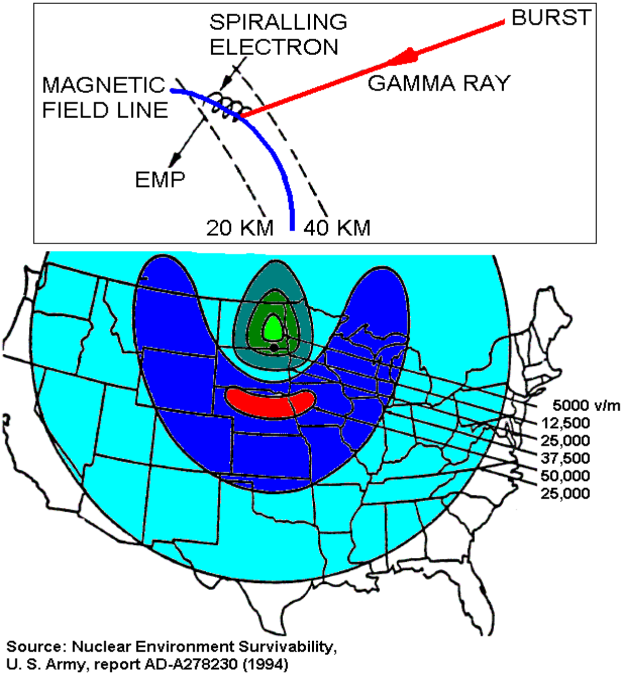
- **US – Starfish Prime (1962)**
  - **1.44 Mt burst, 250 mi altitude over Johnston Island in the South Pacific**
  - **5.6 kv/m E1 pulse in Honolulu**

- **USSR – Test 184 (1960)**
  - **300 kt burst, 180 mi altitude over Kazakhstan**
  - **1,000 to 1,300 nT/min E3 pulse**
  - **Power station 300 mi distant set on fire by E3 Pulse effects and destroyed within 10 seconds**
  - **2,500 amp current induced in overhead phone line**

Electromagnetic Pulse Man Made and Solar

AGENDA

- Overview of reactor fleet
- “The Big Picture”
- Long-term Grid Loss
- EMP impact on nuclear power plants (US Design)
- Qualitative impact discussion
- Ongoing Research
- Mitigating Strategies
- Conclusions



Source: Nuclear Environment Survivability, U. S. Army, report AD-A278230 (1994)

Electromagnetic Pulse (EMP) Introduction

- Two Types
  - Man-made
  - Natural – Geomagnetic storm
- An electromagnetic pulse (EMP) is a burst of electromagnetic radiation resulting from a suddenly fluctuating magnetic field
- A nuclear bomb detonated hundreds of kilometers above the Earth's surface is known as a high-altitude electromagnetic pulse (HEMP) device
- A geomagnetic storm caused by coronal magnetic eruptions (CME) (associated with solar flares) can create a long-duration pulse that can burn out utility power transformers and cause widespread power outages.
- NRC research efforts 1983 -2010 on the effect of EMP on Nuclear Power Plants (NPPs) concluded that NPPs should be able to achieve safe shutdown following an EMP event.
- The NRC staff also evaluated the applicability of the issue under the NRC Generic Issues Program and the results of the evaluation did not support the need for a Generic Issue at this time.

–

HEMP Wave

- The high-altitude detonation of a nuclear weapon can generate a large electromagnetic pulse (referred to as a high-altitude EMP or HEMP) that is comprised of three components: E1, E2 and E3.
- E1 and E2 refer to the nearly-instantaneous emissions that are most commonly associated with HEMP.
- E1 and E2 can result in damage to electronic components and low and medium voltage electric infrastructure,
- E3, or magnetohydrodynamic electromagnetic pulse (MHD-EMP) can drive low frequency, geomagnetically-induced currents (GIC) in transmission lines and power transformers which can result in voltage collapse and increased hotspot heating in bulk-power transformers.
- The E3 waveform is a long-duration pulse, persisting for hundreds of seconds that induces currents in long power and communication lines, destabilizing or damaging connected equipment such as transformers and solid state communication line drivers.
- **E3 waveform effects are comparable to those from solar geomagnetic effects and are of current interest.**

HEMP Wave Details

- **E1 Pulse – very fast component of nuclear EMP. It is too fast for ordinary lightning protectors and destroys computers and communications equipment.**

- **E2 Pulse – many similarities to pulses produced by lightning. Least dangerous type of EMP because of the widespread use of lightning protection.**

- **E3 Pulse – much slower pulse caused by the Earth’s magnetic field being pushed out of the way by the nuclear explosion or solar storm followed by the field being restored to its natural place. This process can produce geomagnetically induced currents in long electrical conductors (like power lines) which can damage or destroy power line transformers.**

Effects of E1 Pulse

- **E1 Pulse travels at 90% of the speed of light**
- **Peaks after 5 - 10 nanoseconds, over in 1 microsecond**
- **Normal circuit breakers are not fast enough**
- **Circuit boards are highly sensitive compared to electromagnetc devices**
- **Potentially, integrated circuits connected to cables can overheat and give false readings, be damaged or destroyed**
- **Other electromagnaetic devices susceptible to damage**

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Transmission System (SCADA)

- Supervisory Control and Data Acquisition (SCADA) systems are electronic control systems that control electrical transmission and distribution, water management and oil and gas pipelines across the country
- Tests indicate that the electronics could experience high (100 to 1kA) ampere currents during an E1 pulse, impacting a significant portion of transmission systems

Effects of E2 Pulse

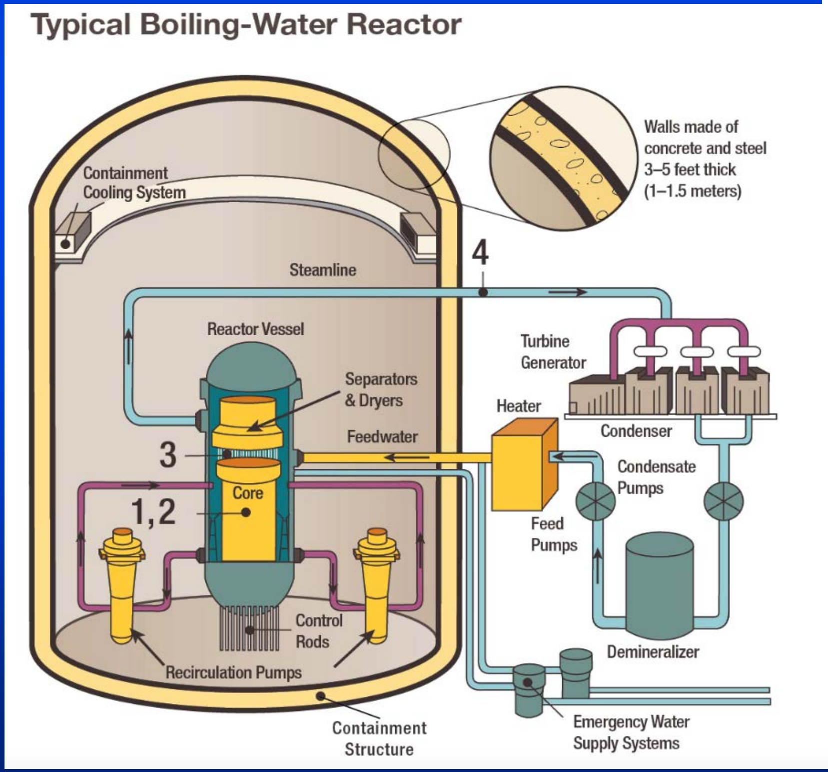
- **E2 Pulse is very similar to the electromagnetic pulse produced by lightning.**
- **Due to the widespread use of lightning protection technology, E2 probably is the least dangerous type of EMP**
- **Effect would be similar to multiple lighting strikes hitting power lines simultaneously**
- **Damage from E1 Pulse could potentially degrade lightning protection resulting in the E2 wave becoming more damaging**

Effects of E3 Pulse

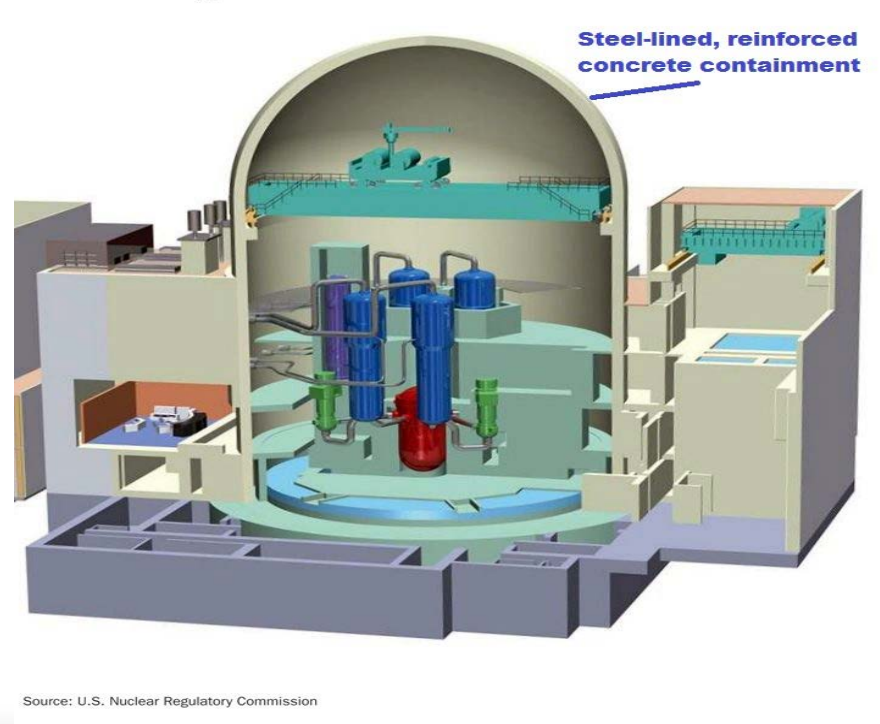
- **E3 Pulse lasts from tens of seconds to several minutes**
- **Produces direct current similar to Ground Induced Currents (GIC) in conductors from Solar storms**
- **Long distance electrical power transmission lines are excellent conductors**
- **The longer the conductor and the lower its resistance, the easier the GIC can flow**
- **Direct currents of hundreds to kilo Amps can flow into transformers, potentially causing overheating and fires**

U.S. Fleet of Reactors

- About 100 boiling and pressurized water reactors (~20% of U.S. electric power generation)
- Two new AP1000 reactors under construction
- One small modular reactor design approved



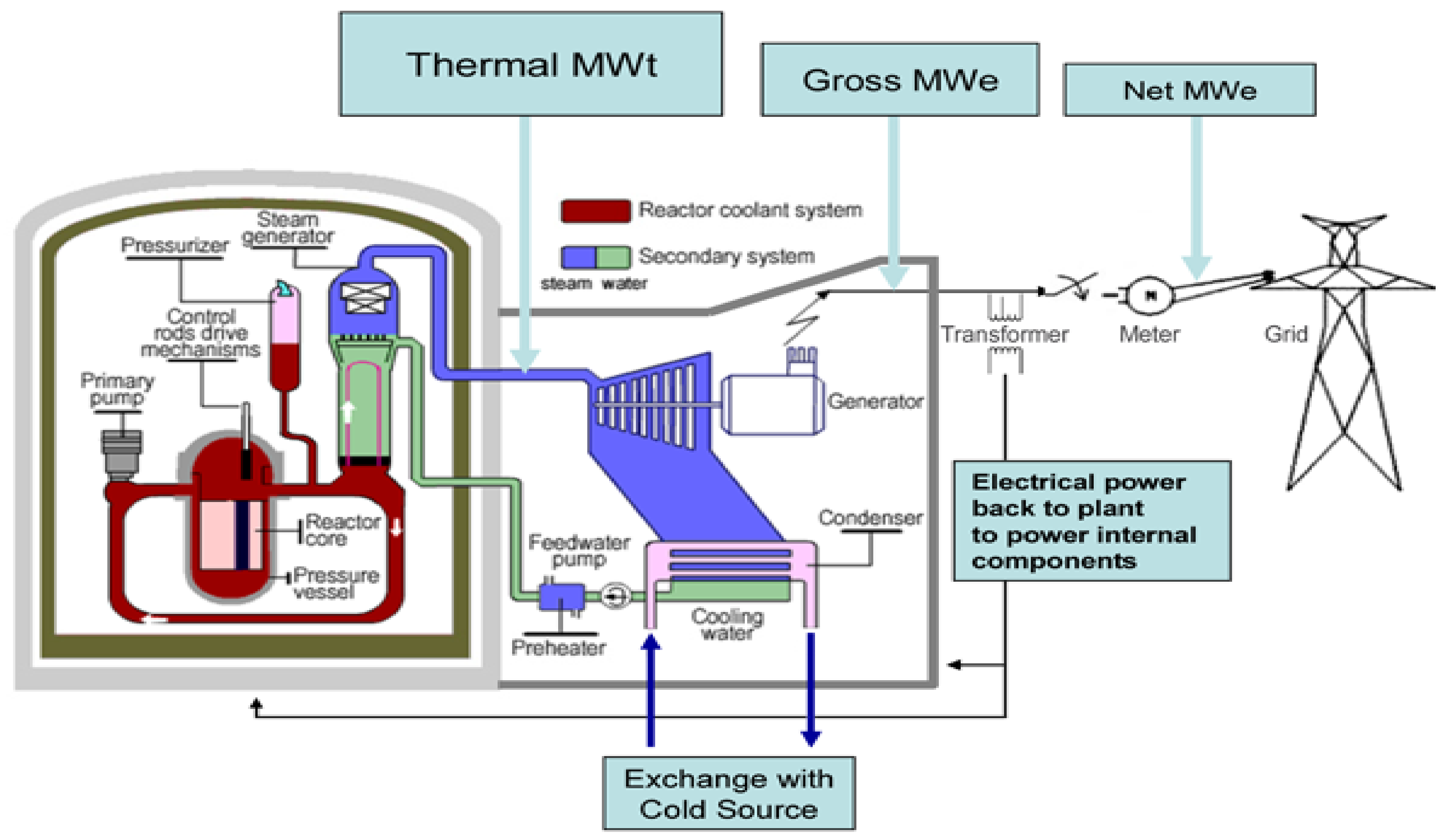
Typical Boiling-Water Reactor



Typical Pressurized Water Reactor

Source: U.S. Nuclear Regulatory Commission

Qualitative Evaluation



Thermal MWt

Gross MWe

Net MWe

Electrical power back to plant to power internal components

Exchange with Cold Source

The Big Picture

- Nuclear power plants would achieve safe shutdown following an HEMP event
- Continued core and spent fuel pool cooling will be required essentially indefinitely
- Logistic support to maintain core cooling will be required (diesel fuel, water, personnel, etc.)
- Industry continues to evaluate HEMP issues at national and international level

Long-term Loss of Grid

- All nuclear power plants are designed for safe shutdown following a total loss of transmission system or offsite power
- Reasonable level of confidence that safety systems required for plant shutdown and extended core cooling functions will be available post-HEMP event
- Onsite-generated electric power must continue (multiple emergency diesel generators and batteries)
- Longest NPP grid-related outages in USA (severe weather) have lasted less than 14 days

Long-term Loss of Grid (cont.)

- Onsite diesel fuel supply required by regulations, varies among plants based on plant-specific conditions.
- Emergency diesel generators are robust, usually not operating, located in robust structures, expected to survive.
- Post-Fukushima, US NPP operators have implemented measures to extend battery life and have auxiliary equipment (such as pumps and diesel generators) available from remote locations or secure onsite facilities to support core cooling and spent fuel pool cooling – not energized, but robustness in HEMP environment likely not specifically studied
- NPP operators need to make arrangements for resupply of diesel fuel – effects of long-term grid loss on such arrangements should be considered.

Some Considerations for Extended Grid Loss

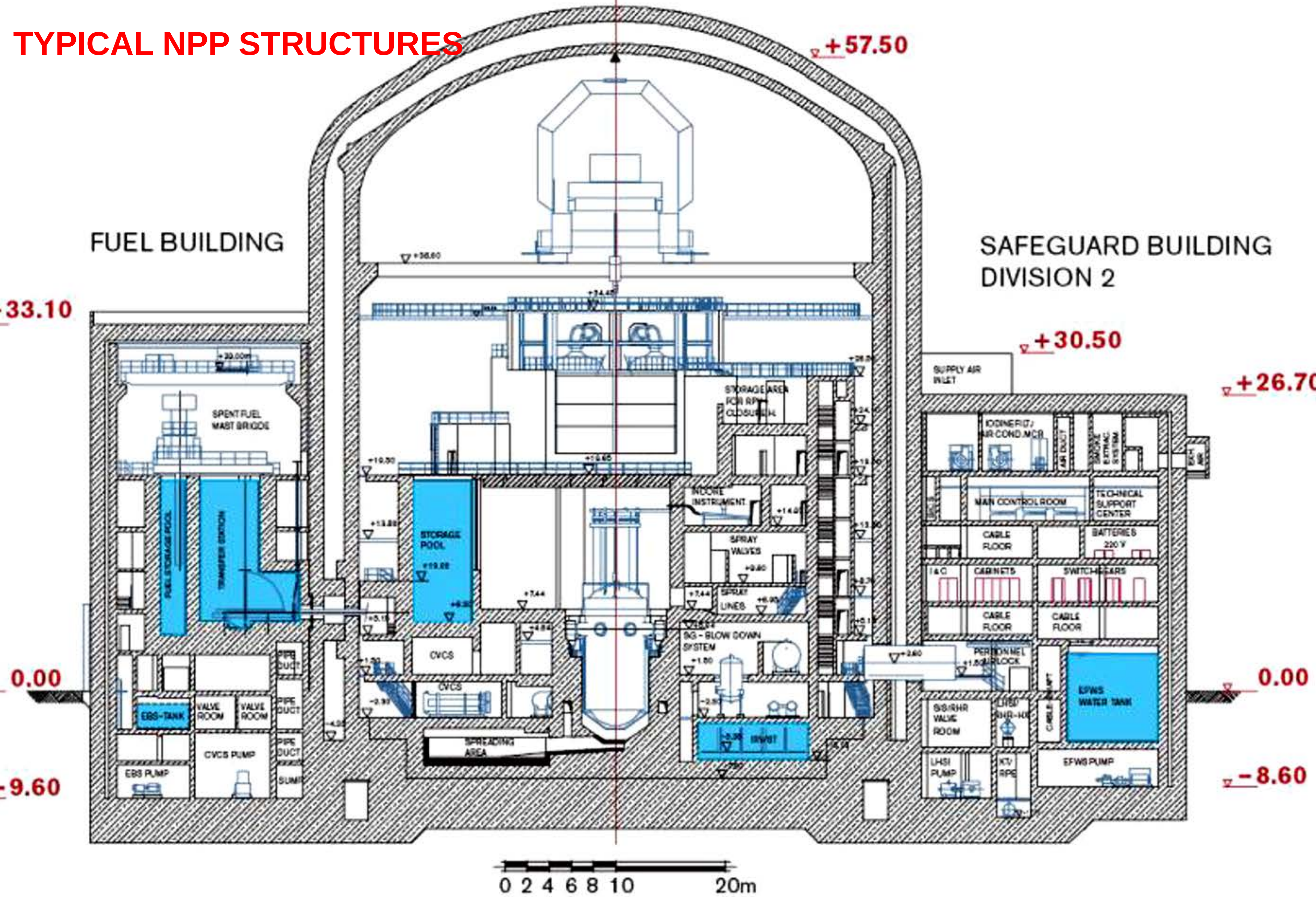
- Consumables such as fuel oil and lube oil for the EDGs need to be replenished after days/weeks
- Treated makeup water may be needed at some point –
- Nuclear power plants require significant numbers of personnel (operators, mechanics, etc.) even in shutdown condition
- Plant Safety and Security must continue to be maintained

Design Bases of NPPs

US regulations focus on safely shutting down a NPP and maintaining safe shutdown conditions – require:

- Capability for safe shutdown given loss of all offsite power (i.e. the grid)
- Capability to maintain safe shutdown given a loss of offsite and onsite AC power for at least 4 hours (Station Blackout). Post-Fukushima, this capability has been extended to more than 7 hours
- Equipment required for safe shutdown of the plant defined as important to <u>safety</u> be able to withstand specified environmental and external events
- <u>Non-safety</u> equipment not relied upon for safe shutdown

TYPICAL NPP STRUCTURES



Salient Design Features

- CONTAINMENT DESIGN: can be up to 6 to 10 mm steel liner, 1 metre annulus and 1-1.3 metre thick reinforced concrete structure

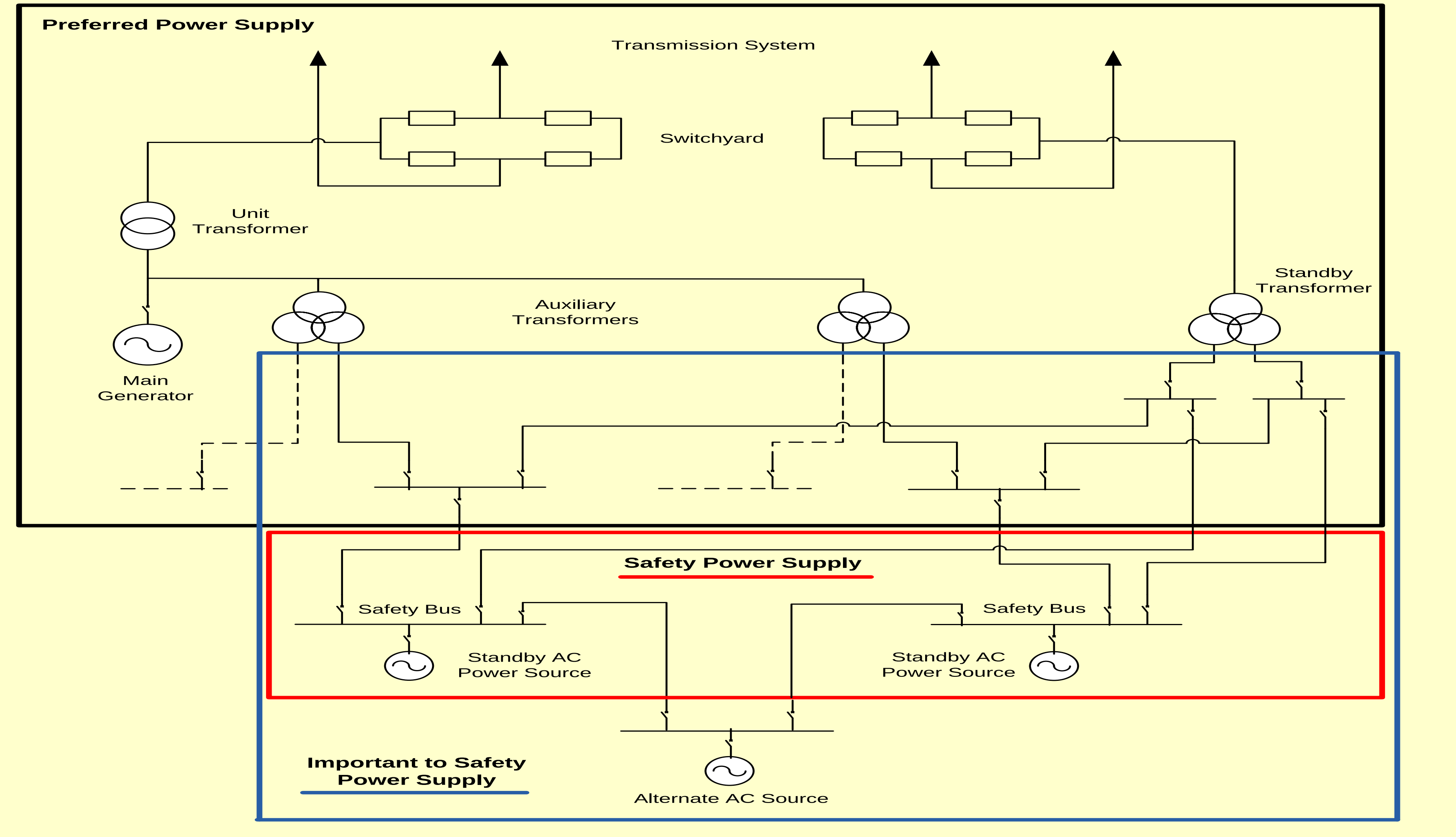
- REACTOR AUXILIARY BUILDING (RAB): Not designed to withstand high pressure so no steel liner. A reinforced concrete structure and mat foundation supports a structural steel and reinforced concrete frame - mainly reinforced concrete walls and floors. Designed to minimize radiation leakage to the environment – hence expected to attenuate gamma ray penetration

- FUEL POOL BUILDING: Similar to RAB with water-filled stainless steel lined concrete pool

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Equipment Required for Power Generation

Large non-safety equipment required for plant start up and power operation..



HEMP Assumptions

- Consider E1 Wave: a peak lasting a few nanoseconds and then decaying gradually over a period lasting hundreds of seconds

- Expect the E1 and E2 voltages to cause breakdown "flashover" paths within powered-up systems

- E3 and GIC can cause direct damage to equipment connected to long lines, and also cause transformers to saturate resulting in harmonic currents which can damage equipment

Expected HEMP Impacts

Conservative Assumptions:

- Loss of offsite power and damage to ‘exposed’ non-safety equipment, including control and protective functions of the main generator transformers, breakers and turbine systems
- Expect mechanical systems to function
- Assume (non-safety) automatic digital and analogue control and instrumentation systems associated with power production to fail

Expected Plant Response

- Generator trips on over speed (loss of Load)
- Reactor trips and control rods insert
- System pressures increase and actuate automatic injection systems
- Standby power supplies and important safety systems expected to survive HEMP due to inherent design features of NPP
- Safety significant systems generally NOT connected to external power sources

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Expected Plant Response (Cont.)

- Safety systems designed to fail in ‘fail safe’ mode
- Automatic actions designed for large breaks (LB) in piping systems
- A HEMP event will not result in LB. Manual actions can be taken to start critical equipment

Additional Perspectives

- The HEMP signal may penetrate directly into the plant interior, creating diffuse fields, which then couple with the interior plant cabling to induce current on those cables
- The HEMP can interact with the external power grid to which the plant is connected, and currents induced there could penetrate into the plant on the power lines feeding plant systems
- The HEMP might induce currents in power and instrumentation lines which interconnect various plant buildings and systems

Expected Outcomes

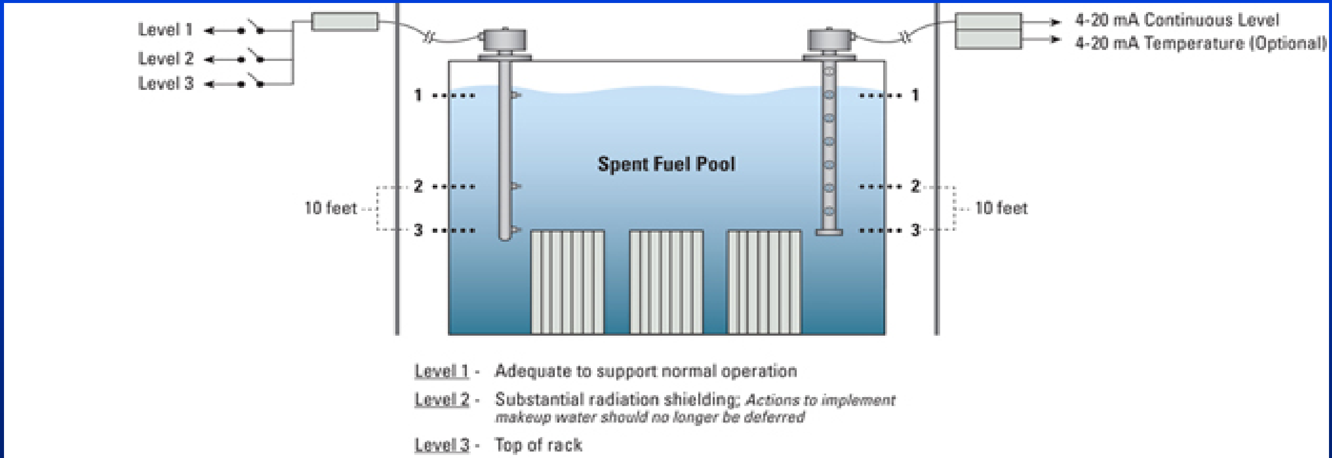
- Do not anticipate severe damage or significant degradation of equipment required for safe shutdown of the NPP because:
  - All equipment designed to withstand external events such as seismic, tornadoes, severe weather etc.
  - Robust electrical design compared to commercial power system requirements. Power cables have shielding that offer some protection from HEMP
  - Majority of equipment required for safe shutdown of the plant is de-energized (isolated from external power sources) in a standby mode

Expected Outcomes (cont.)

- Some critical cooling water and HVAC systems operating
- All equipment located in steel reinforced concrete structures which help in attenuating and diffusing electrical currents and magnetic fields. The containment building has a concrete and steel liner that (typically) provides 3 ft. thick barrier
- The onsite power AC systems are in standby mode and not connected to external power sources. In the event that a power source is being tested, the exposure time is less than 5 to 10 hours a month and less than 30 hours once every 18 months. Only one source is tested at a time.

Spent Fuel Pools

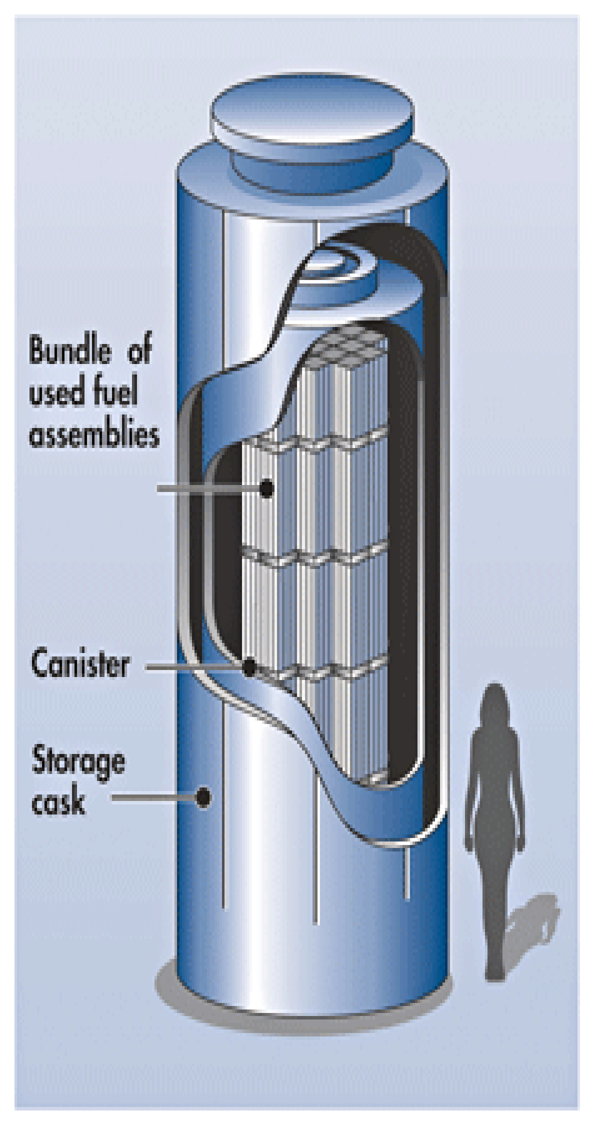
- Spent Fuel pools needed to store recently offloaded (spent) fuel for some duration (a few years) until radioactivity decay has decreased to a level acceptable for dry storage
- The pools may not be protected by redundant emergency makeup and cooling systems or housed within robust structures providing substantial HEMP protection
- Fuel pool cooling can be manually initiated. Time available (at least several hours and usually much longer) prior to boiling in the fuel pool if cooling is not restored – substantial additional time to restore cooling/add makeup water after boiling begins



Level 1 - Adequate to support normal operation
Level 2 - Substantial radiation shielding; *Actions to implement makeup water should no longer be deferred*
Level 3 - Top of rack

Dry Cask Storage

- Passive cooling and radiation shielding are possible because these casks are designed to store only older spent fuel. This fuel has much lower decay heat than freshly discharged spent fuel as well as smaller inventories of radionuclides
- Irradiated fuel casks can withstand environmental disasters that spent fuel pools cannot, as evidenced by the continued function of the dry casks at Fukushima. The casks survived the 9.0 quake and continue to protect the irradiated fuel, even though the tsunami flooded them
- Almost every US nuclear reactor site has dry storage implemented or has near-term plans to implement dry storage – does not replace pools at operating reactors



NPP Electrical Design Features

- Cables at NPPs run in metal-enclosed raceways: metal trays and metal conduits
- All equipment in metal enclosures
- Onsite Emergency Diesel Generators in standby mode

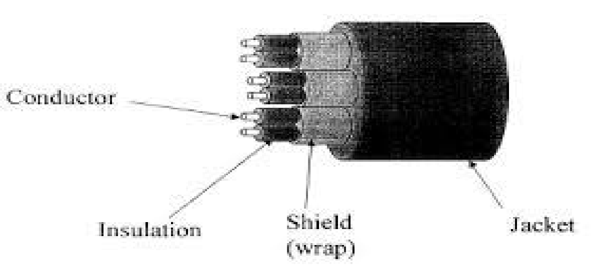
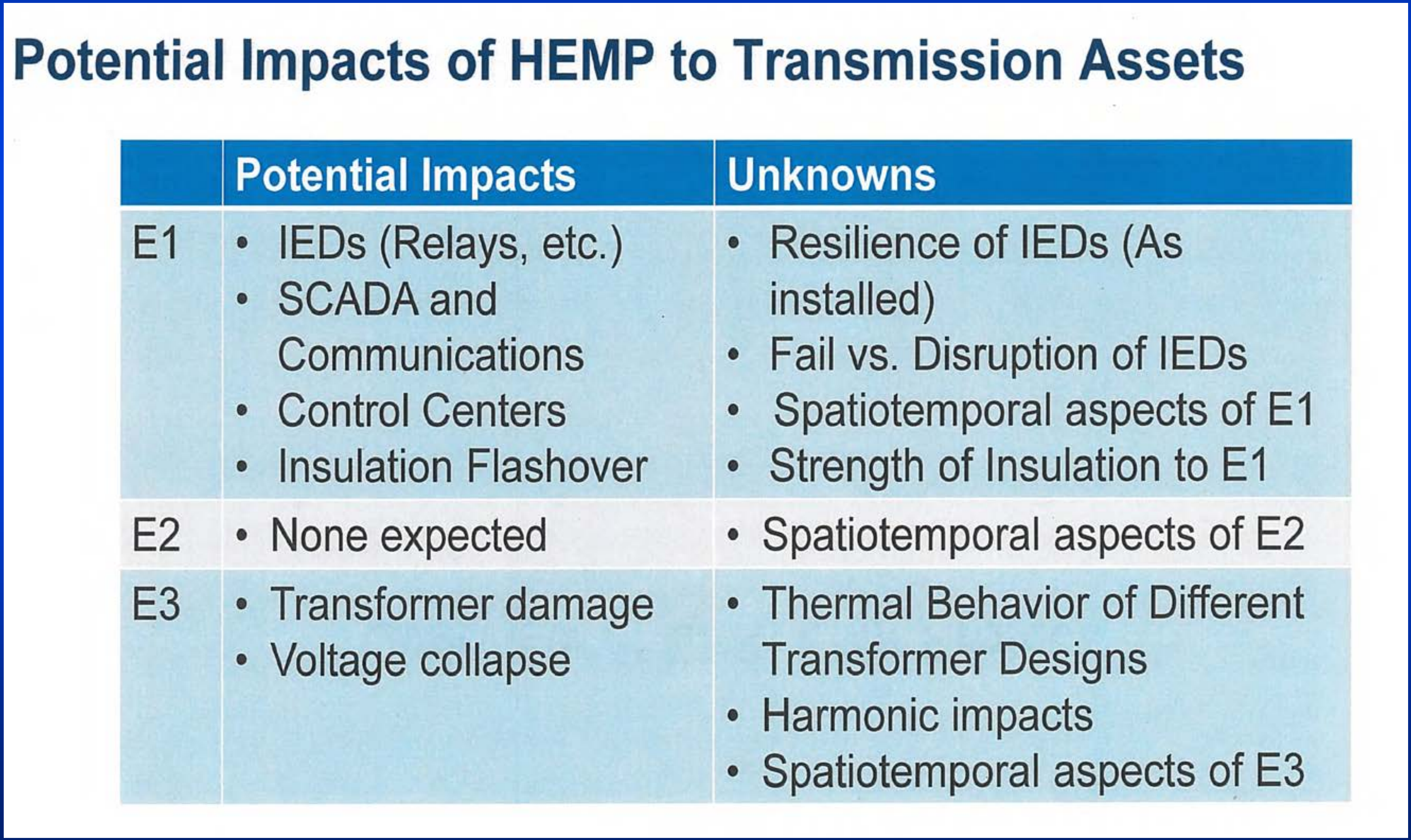


FIG. 2.1. Structure of a twisted pair shielded instrumentation cable (schematic).

Overview of Research

Reference EPRI EMP Project



Potential Impacts of HEMP to Transmission Assets

	Potential Impacts	Unknowns
E1	• IEDs (Relays, etc.) • SCADA and Communications • Control Centers • Insulation Flashover	• Resilience of IEDs (As installed) • Fail vs. Disruption of IEDs • Spatiotemporal aspects of E1 • Strength of Insulation to E1
E2	• None expected	• Spatiotemporal aspects of E2
E3	• Transformer damage • Voltage collapse	• Thermal Behavior of Different Transformer Designs • Harmonic impacts • Spatiotemporal aspects of E3

Field Trials of E1 EMP Mitigation Are Needed

- Potential mitigation options include:
  - Low-voltage surge suppression devices and filters
  - Shielded or fiber optic cables
  - Substation control house design modifications
  - Grounding/bonding enhancements
- Identifying and managing unintended consequences is critical
- Improving designs and understanding cost and long-term asset management also very important

Considerations Based on Industry Research

- Based on industry research and transformer experts - solar storms and HEMP not expected to catastrophically damage large transformers and rotating equipment
- Non-safety control and protective features outside the nuclear island not evaluated for large HEMP event
- Majority of NPPs have digital controls in non-safety systems and are voluntarily transitioning to digital controls for safety systems. Current regulations require EMP consideration at a lower magnitude compared to postulated HEMP event

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

HEMP Hardening Methods and NPP Design

- US and UK Military Standards provide guidance for HEMP hardening – Though NPPs not designed to MIL Standards, some inherent design features meet the recommendations
- Shielding – Enclosure of conductive metal structure – Steel Containment, reinforced thick concrete walls.
- Grounding: Faraday cage around NPP Building. NPP Cables are shielded
- Filtering – Important Controls and Instrumentation powered from Uninterruptible Power supplies
- Surge protection –Transformers

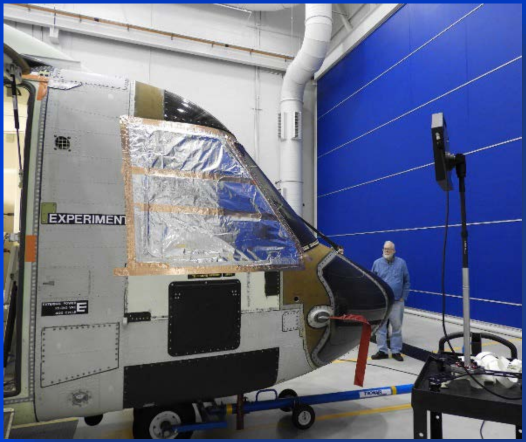
HEMP hardening – metal boxes around electronics and filters on cables and antennas

Shielding

- Faraday Cage
- Point of Entry (POE) Control
- EM Gaskets
- Connector Shells

Interface Design

- Terminal Protection Devices
- Filters
- Current Limiting
- Transformer Isolation

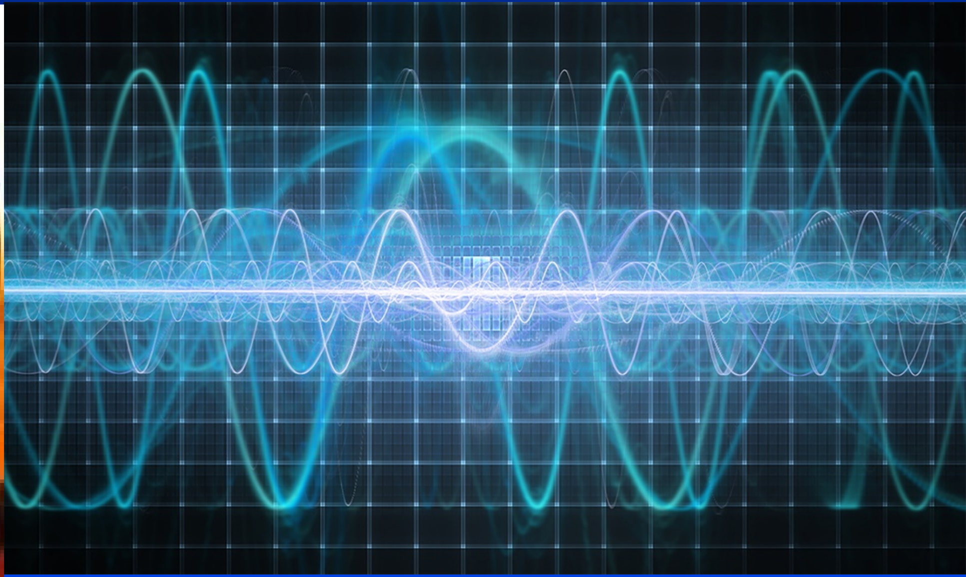


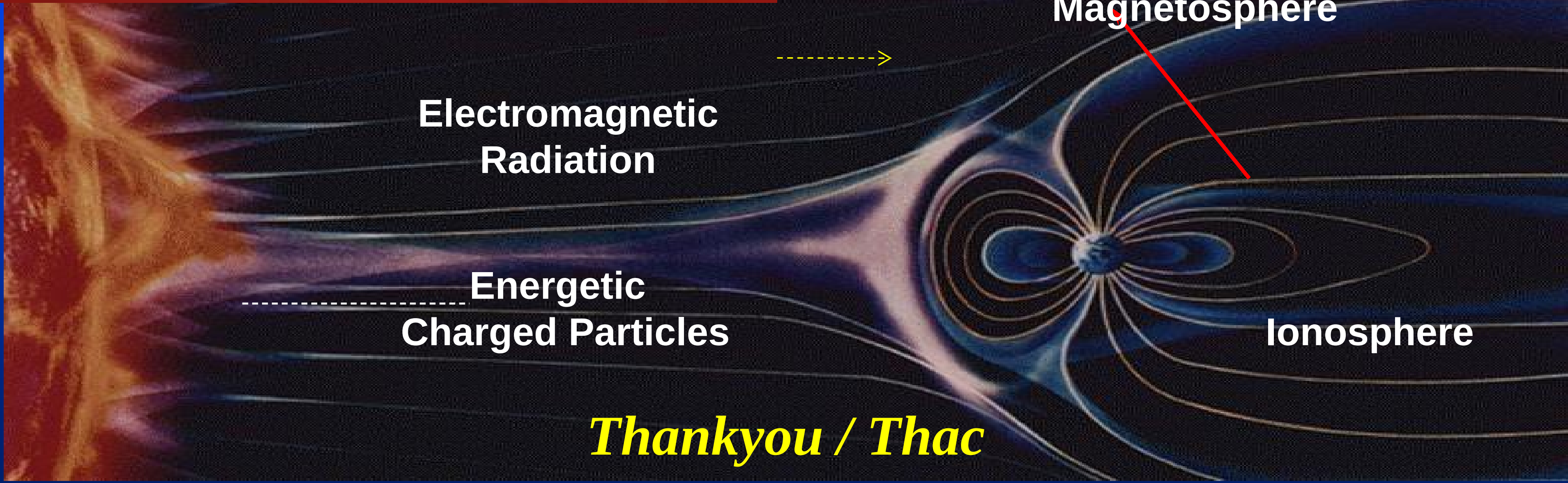
U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Summary

- Characteristics of nuclear weapons detonations well understood
- HEMP threat is real
- Threat can be mitigated by metal boxes around electronics and filters on cables and antennas
- Testing capabilities are available
- Hardening is affordable if addressed up front

Questions / Fragor





Magnetosphere

Electromagnetic Radiation

Energetic Charged Particles

Ionosphere

Thankyou / Thac