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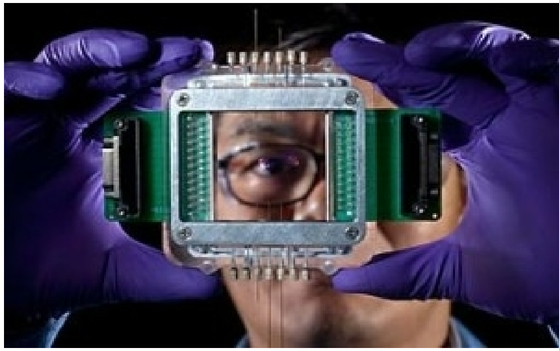

EMP-Resilient Grid
Assess-Optimize-Innovate

Electromagnetic Pulse Research and Capabilities Development at Sandia National Laboratories

Dr. Matt Halligan, 1353

November 8, 2019

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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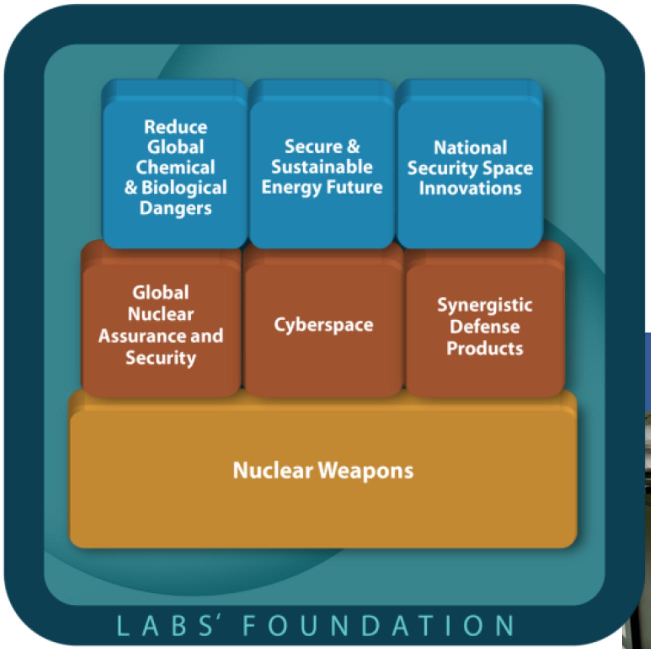
Outline

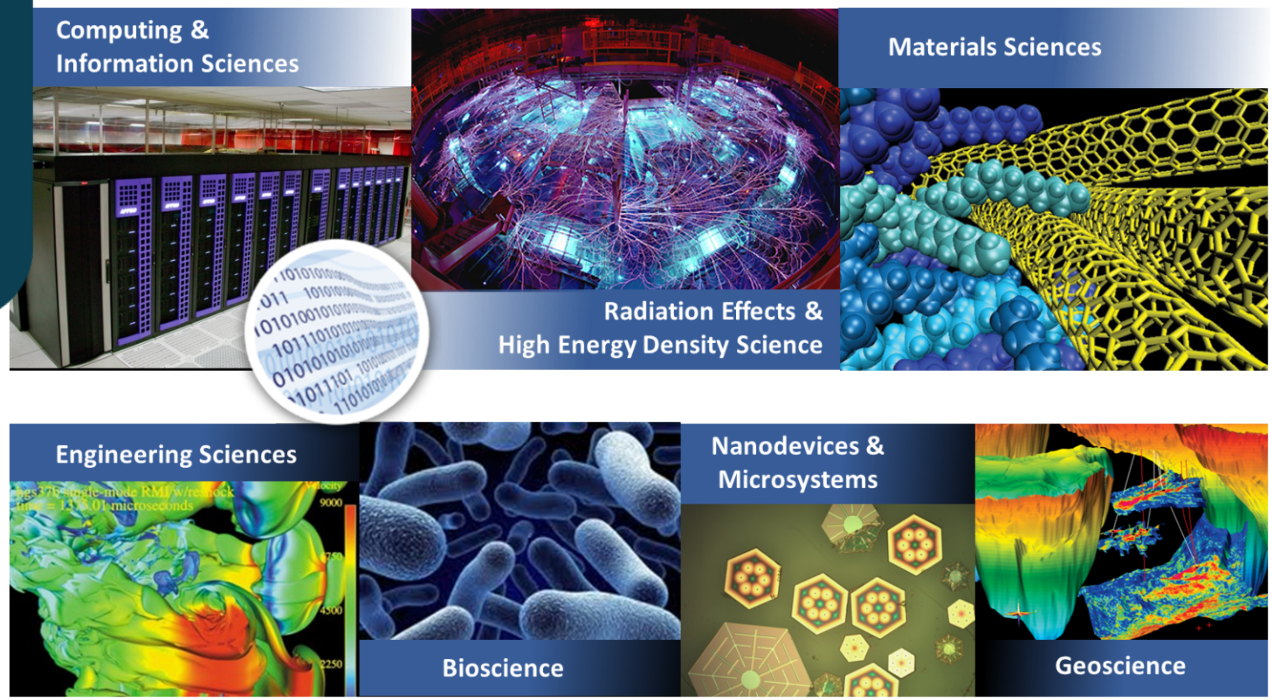
- Sandia National Laboratories (SNL) Background
  - Mission areas and group background
  - Electromagnetic test capabilities
  - Electromagnetic Pulse (EMP) history
- EMP Laboratory Directed Research and Development (LDRD) Project Overview
  - Research thrust areas
  - Scope of research and analysis flow
  - Technology development and coupling results
  - Grid modeling approach
- Center for EMP/GMD Simulation, Modeling, Analysis, Research, and Testing (CE-SMART) Project Overview
  - Background
  - Executive order
  - Project structure
  - Next steps and summary

SNL Mission Areas



Program Management Units

- Nuclear Weapons
- Defense Systems & Assessments
- Energy & Climate
- International, Homeland & Nuclear Security



Strong research foundations play a differentiating role in our mission delivery

Group 1350 Structure – Electrical Sciences

Electrical Sciences

Electrical System Modeling
(1355,1356)

Coupled EM and Full System Models

Electromagnetic Effects
(1352, 1353, 1354)

- *Circuit/Devices codes*
- *Circuit/device mod/sim*
- *Model extraction*
- *Device aging, COTS evaluations*

QASPR

- *EM codes*
- *Modeling/simulation*
- *EM/RF experiments*
- *HV science & experiments*
- *Advanced power systems*

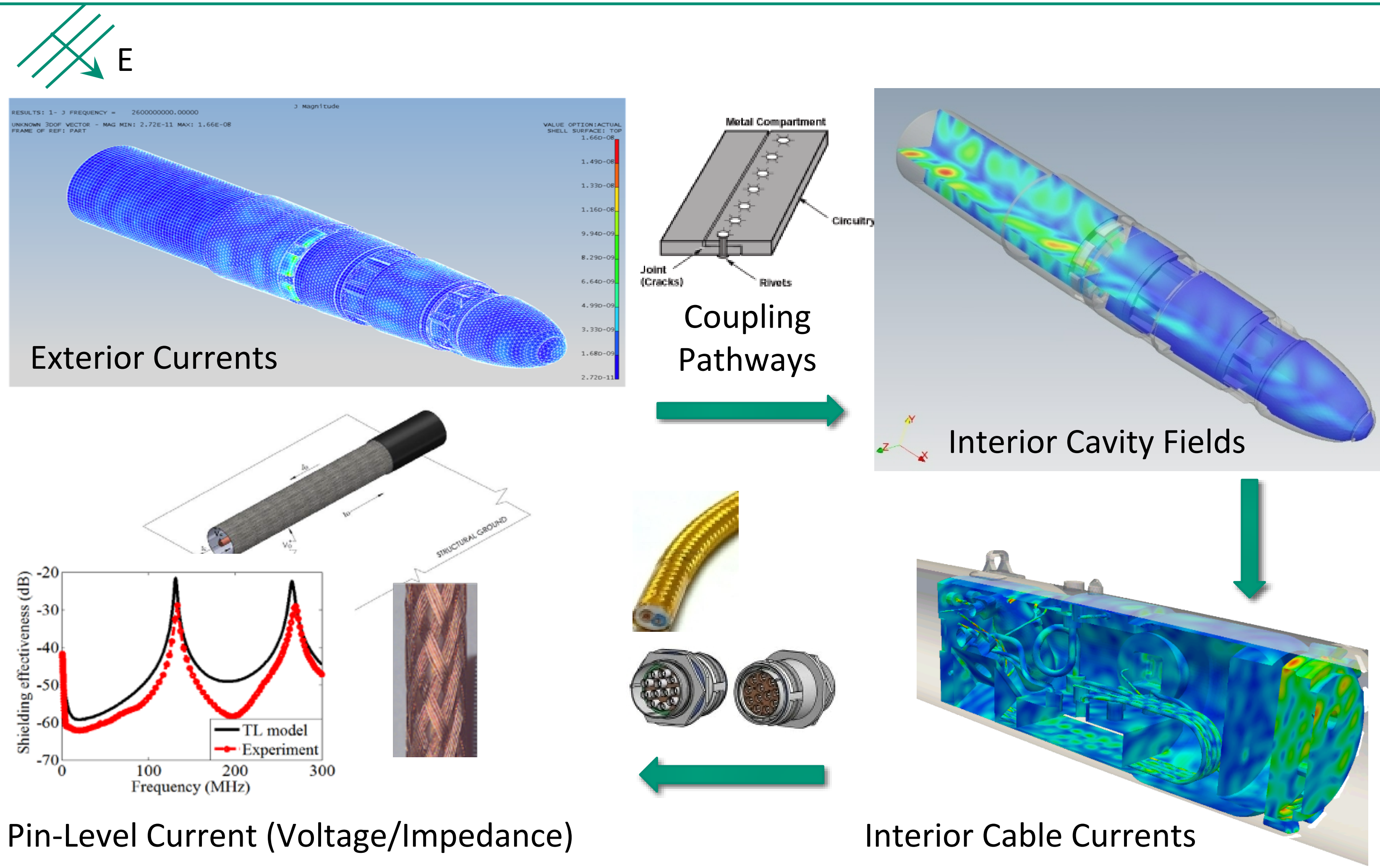
Plasma/Radiation Effect Sciences
(1351)

SGEMP / SREMP

- *Plasma physics codes*
- *System generated EMP and Source region EMP analysis*

eigen · EMPHASIS · Xyce · CHARON

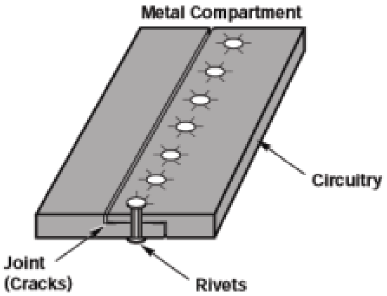
Electromagnetic Modeling Examples



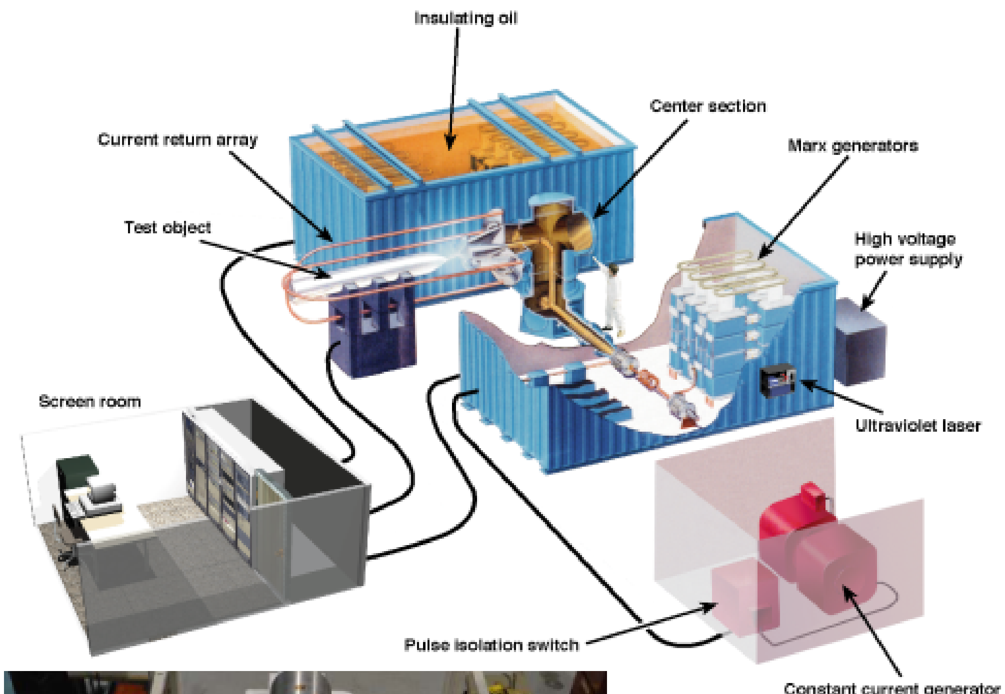
Visualization of interior fields can guide testing configurations

EM Testing Capabilities in 1350

- Weapon electromagnetic (EM) qualification
- Research & development activities
  - Improving qualification methods (“margins and uncertainties”)
  - Characterize phenomenology
  - EM model validation
  - Field measurements and models of environments (RF, ESD, etc.)
  - High voltage environments
    - Electrical arc formation and breakdown
    - High voltage standoff
    - Phenomenology of lightning arresters
    - Lightning current effects on “materials”



Sandia Lightning Simulator (SLS)



Test volume:

- Bombs, RV/RBs or similar sizes

Environments:

- Full-threat lightning (direct-attach and nearby lightning)
- Dual-stroke, with or without continuing current

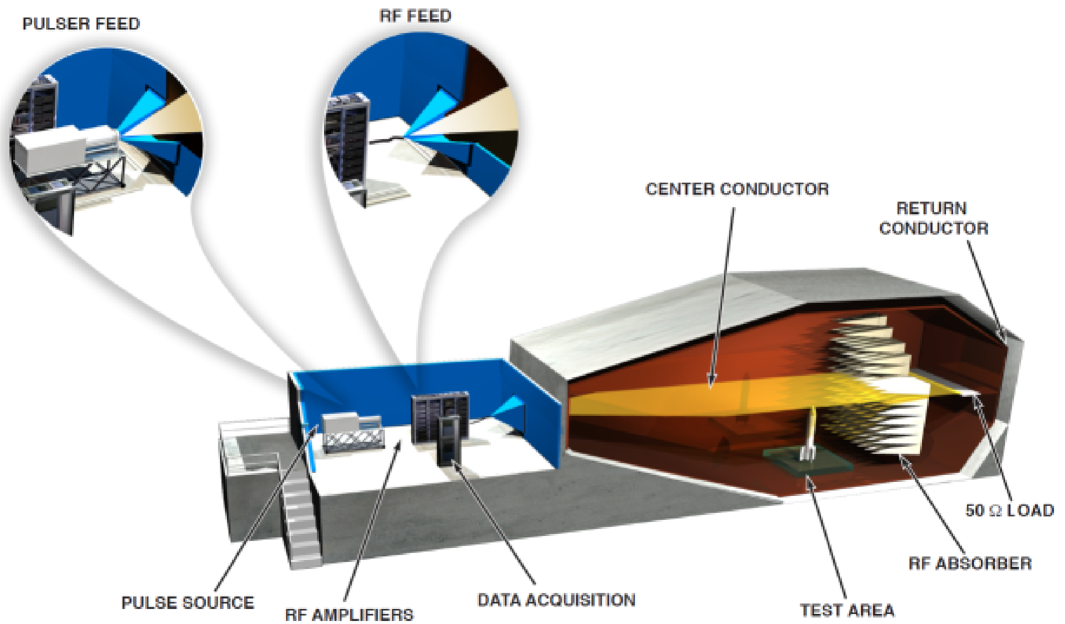
Specs:

- Peak current – 200 kA (99^{th} percentile)
- Min current – 30 kA
- Current rise time: 1 to 5 μs
- Current rate of rise: 200 kA/μs, max
- Pulse width (@50% level): 50 to 500 μs (dependent on load impedance)
- Number of pulses: 1 or 2
- Variable pulse interval
- Continuing current 100s A for up to 1 s

Capacity:

- 4 test/day (typical capability)

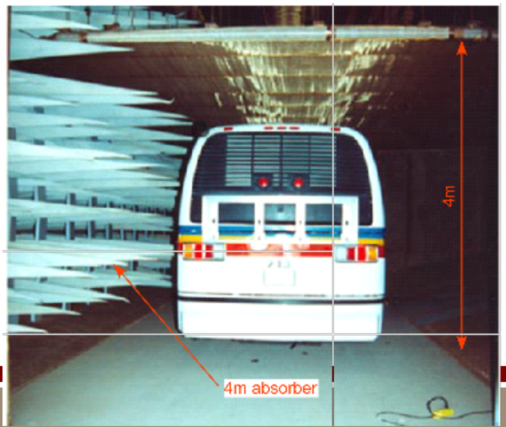
Electromagnetic Environments Simulator (EMES)

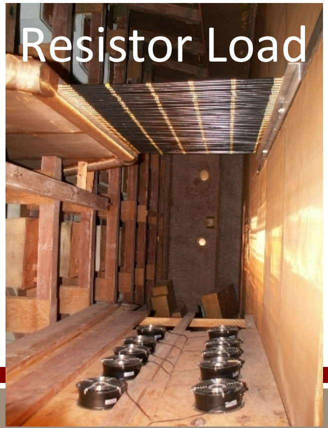


Test volume:
- 4 x 4 x 11 m (approx.)

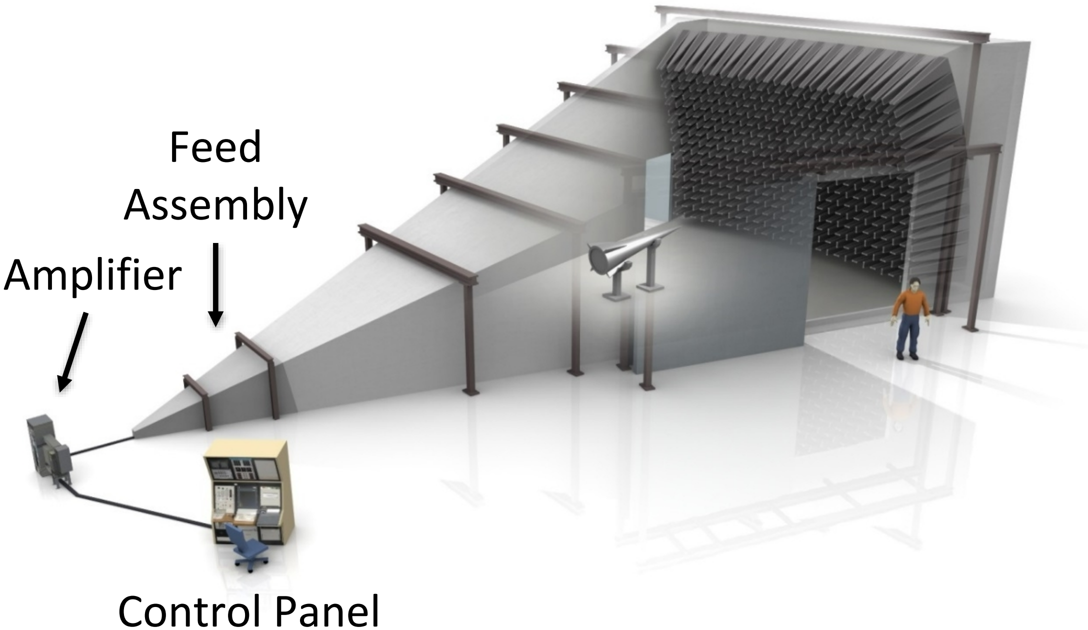
Environments:
- High altitude EMP: 30 to 250 kV/m
- Plane-wave RF (CW): 100 kHz – 100 MHz at 125 V/m
- Rolls off to 100 V/m at 250 MHz

EMP capacity:
- 2 shots/day (max voltage)
- 4 shots/day (nominal)





4.5 m Gigahertz Transverse EM Cell (GTEM)



Test volume:

- 4.5 x 3.7 x 3.7 m (approx.)

Environments:

- Max EMP amplitude: 133 kV/m (future capability)
- Plane-wave RF (CW) at 4.5 m septum height:
    - 10 kHz – 1 GHz at ~100 V/m
    - 1 GHz – 4.2 GHz at ~50 V/m
    - 4.2 GHz – 18 GHz at ~25 V/m

Reverberation Chamber

Test volume:

- 4 x 7 x 11 m (approx.)

Environments:

- Welded aluminum chamber, Q ~ 100k – 1M
- Statistical RF environments (modes, incidence angles, field polarizations, field magnitudes)
- Frequency range: 80 MHz – 40 GHz (200 MHz typical lower bound limit)
- Field strength at max forward power:
  - ~ 700-1100 V/m avg., 200 MHz – 18 GHz
  - ~ 130-200 V/m avg., 18 – 40 GHz

Semi-anechoic Chamber

Test volume:

- 6.3 x 4.5 x 3.1 m

Specs:

- Typically used for emissions testing
- MIL-STD-461F compliant
- Frequency range: 10 kHz – 40 GHz
- 4 x 7 ft entry personnel entry door

Abbreviated SNL History with EMP

- Early history: nuclear weapons development
  - Founding as LANL Z Division (1945)
  - EMP testing of various weapons systems
  - Analysis of nuclear tests (1962 Starfish Burst)
- Advancements in EM modeling research
  - Enclosure and cable coupling (1994-present)
  - Fast simulation tool suite for EMP coupling (2013-present)
- Recent history: EMP and electric grid impacts
  - Congressional EMP Commission measurements (2003-2004)
  - Urban EMP infrastructure modeling (2012-2016)
  - Tri-lab EMP reports (2017, 2018)
  - **EMP-Resilient Electric Grid for National Security Grand Challenge LDRD (2018-2020)**
  - **Center for EMP/GMD Simulation, Modeling, Analysis, Research, and Testing (CE-SMART) (2018-present)**

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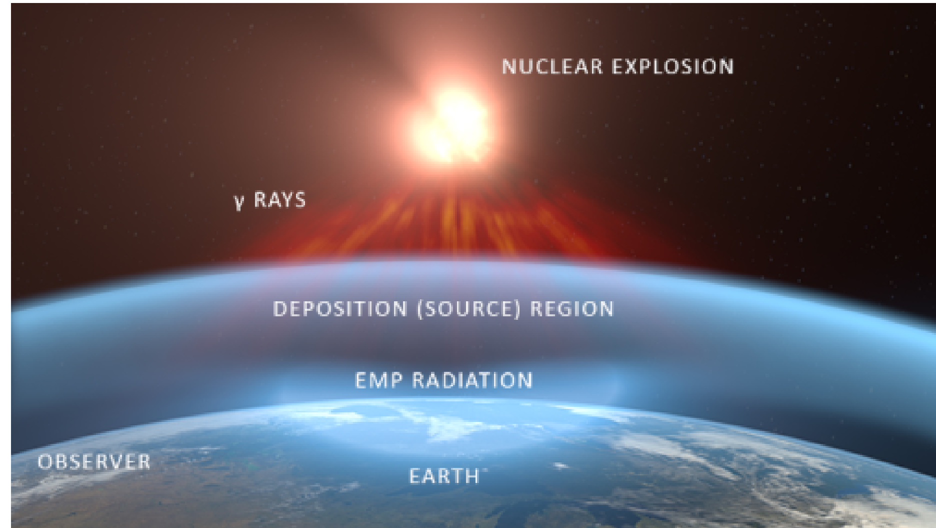
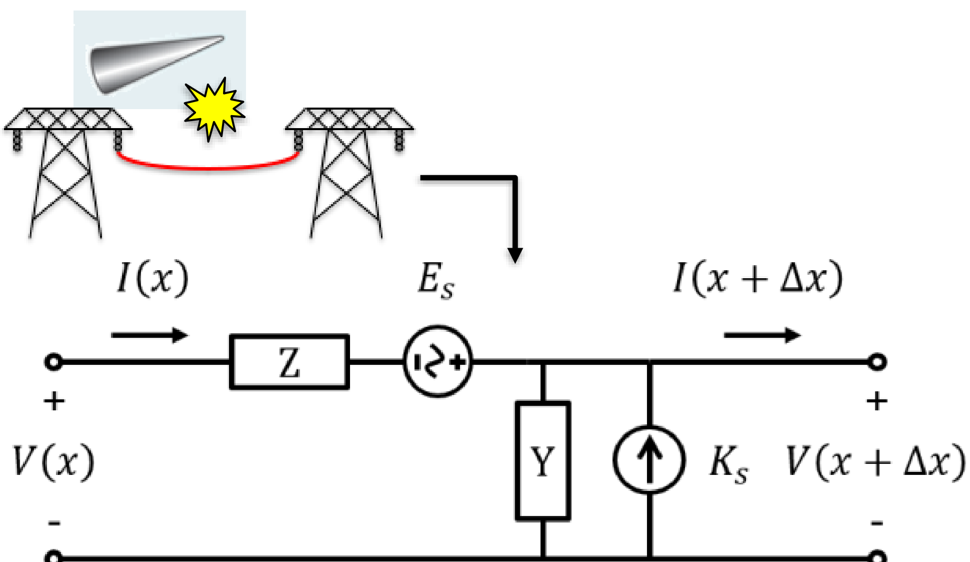
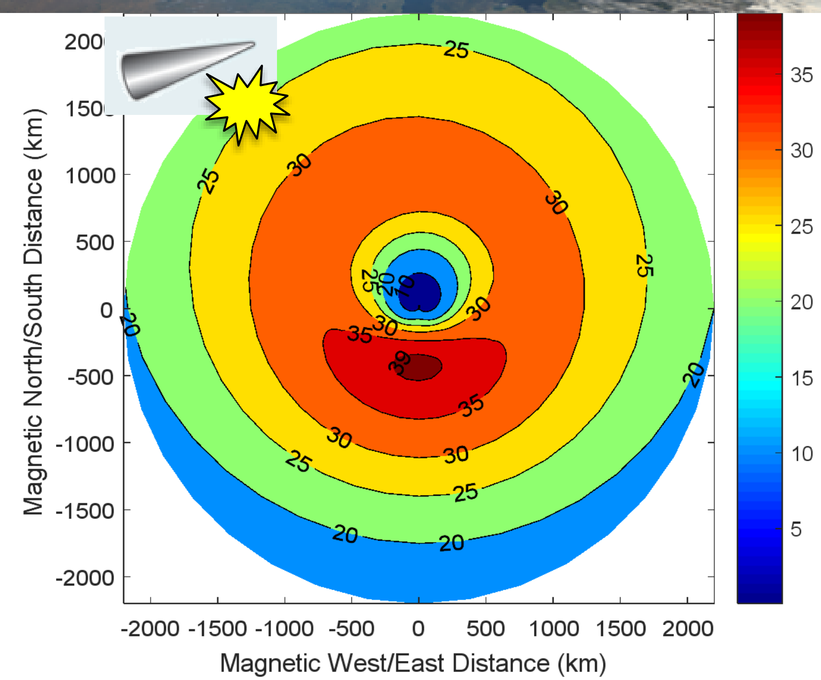
Electromagnetic Pulse Definitions

- Acronyms
  - HEMP = high altitude EMP
  - SREMP = source region EMP
  - SGEMP = system generated EMP
- Research focus on HEMP
  - Resulting from nuclear weapon
  - Burst height > ~30 km
  - No ionizing radiation at Earth's surface

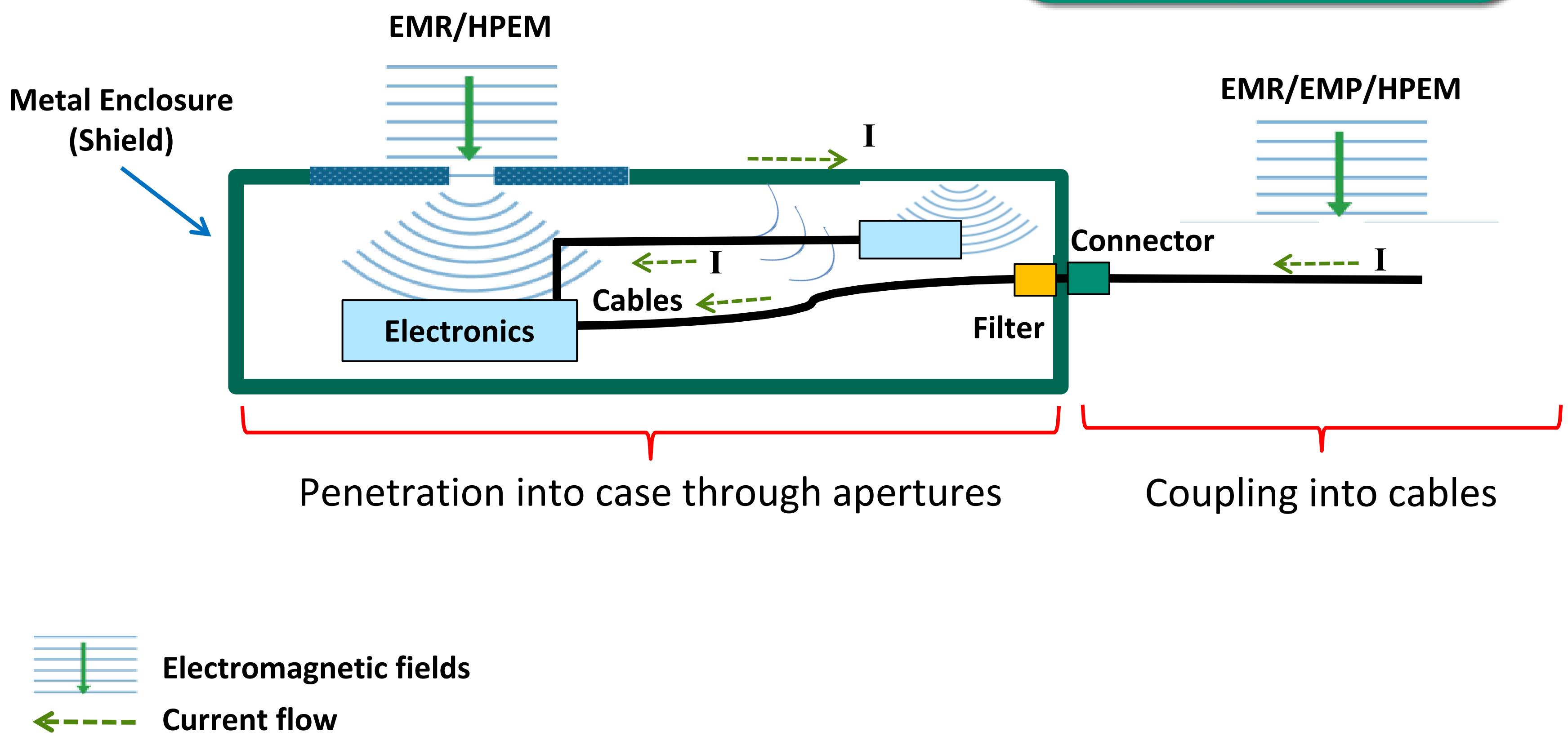






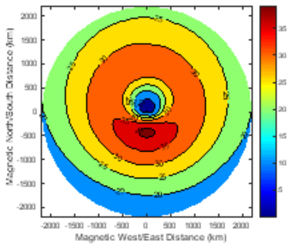
Electromagnetic Coupling Review

Threats include:
1. EM Radiation (EMR)
2. EM Pulse (EMP)
3. High-Power EM (HPEM)

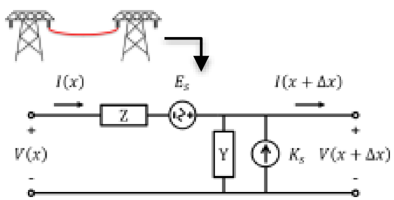


Sandia's Lab-Directed R&D Approach: Three Integrated Thrusts

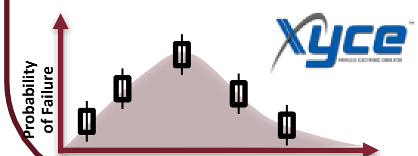
Thrust 1
Vulnerability Assessment



Environments



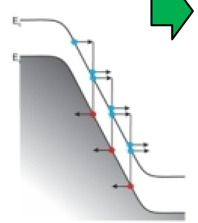
Coupling



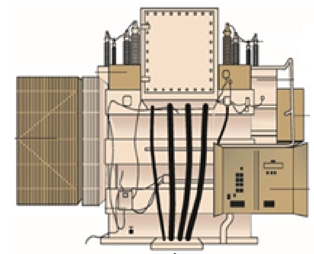
Failure Analysis

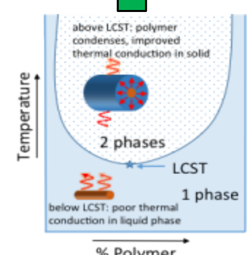
Thrust 2
Material & Device Innovation

EMP hardened assets



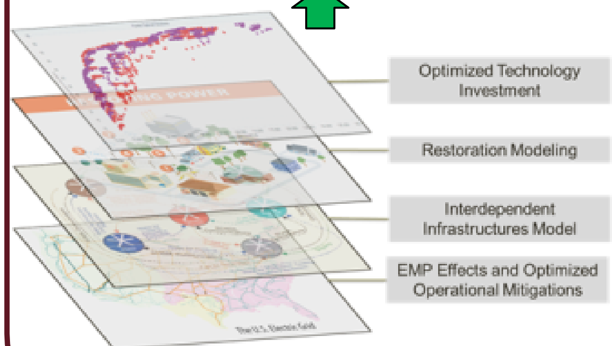
Avalanche Breakdown in a Wide Band-Gap diode





Design New Component Materials to Withstand EMP Effects

Thrust 3
Optimal Resilience Strategies



Modular Multi-Layered Modeling Approach

R&D

- Large scale coupling modeling with significant number of unknowns
- Component response and failure estimation to EMP waveforms

R&D

- Develop Wide Band-Gap EMP arrester
- LCST Polymers for thermal management during E3/GMD

R&D

- EMP effects assessment w/ large scale stochastic, AC dynamic optimization
- Risk mitigation by tech deployment, operational mitigation & optimal restoration

Generalized HEMP Waveform

- Openly available curve from IEC and military standards
- Polarization and incidence angle must be assumed
- Los Alamos National Laboratory (LANL) E1 and E3 environments also available
- E2 not well known but thought to have less significant impact

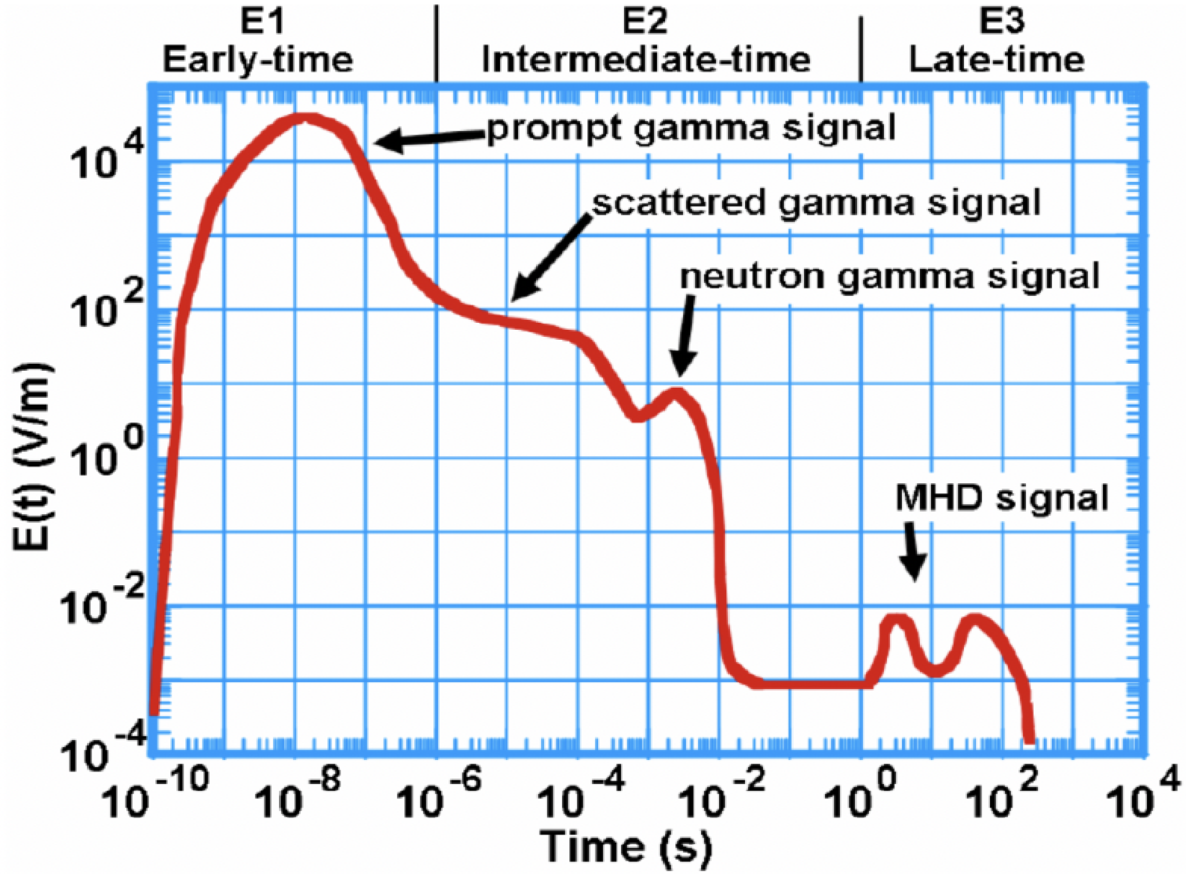
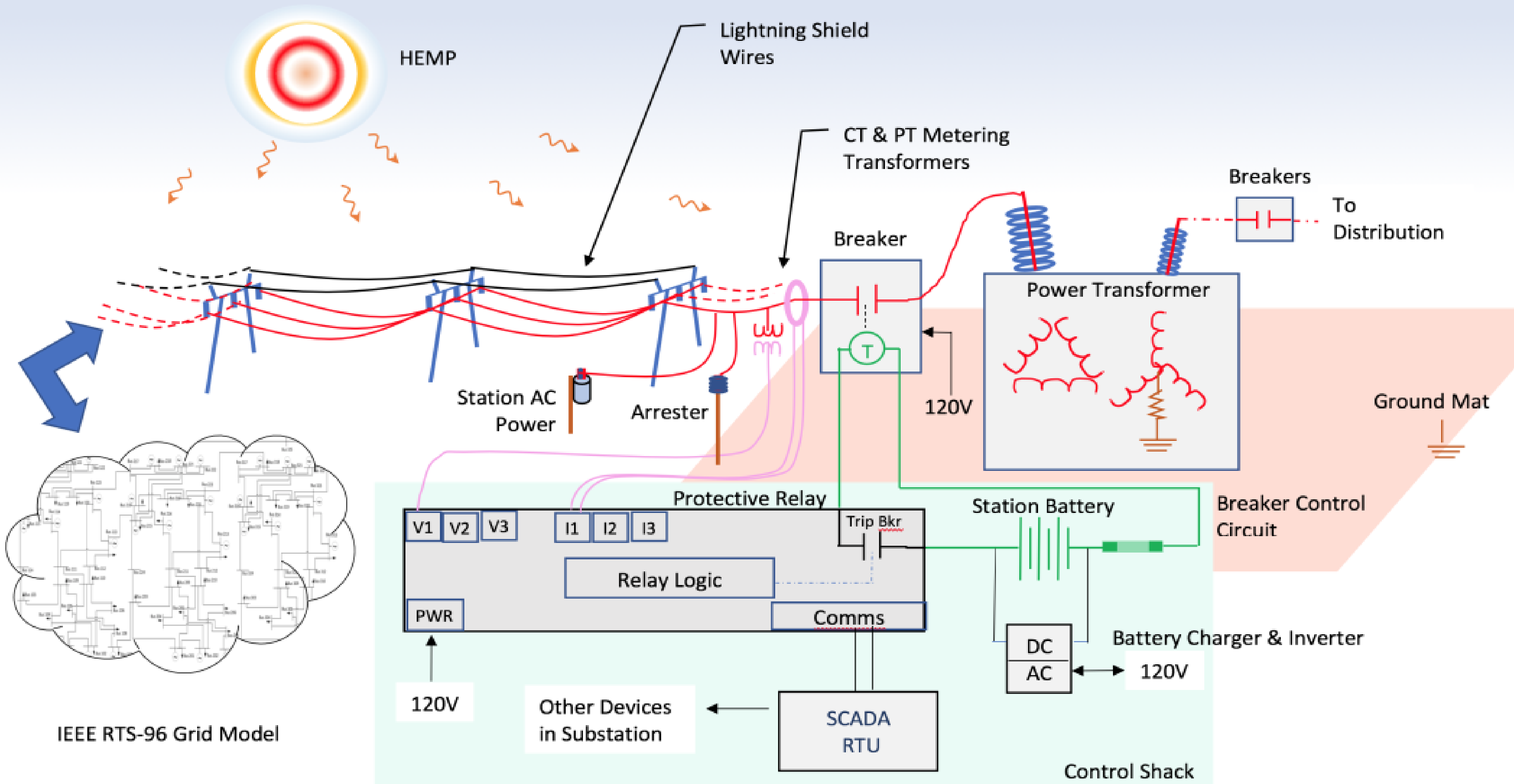
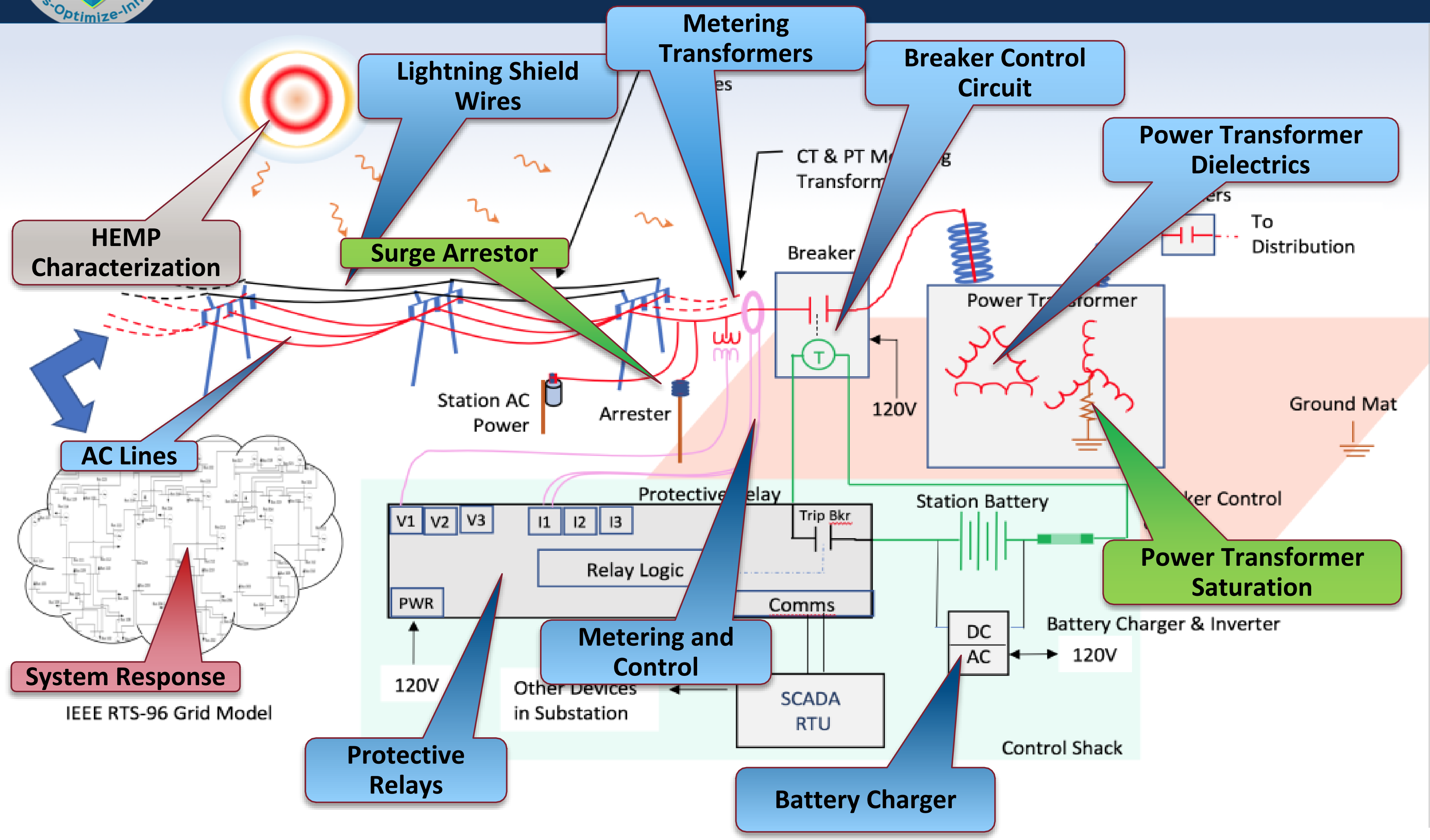


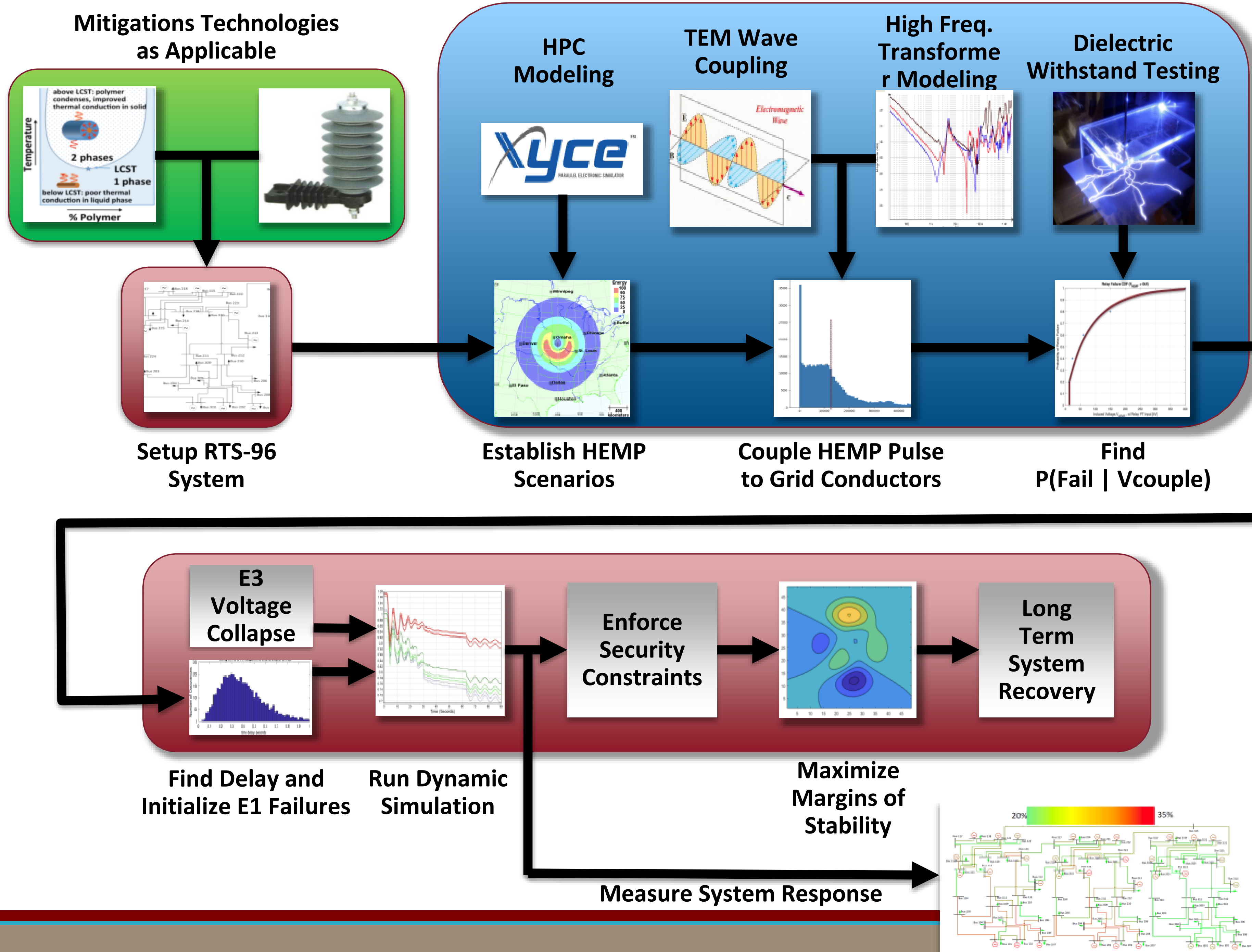
Figure Reference: E. Savage, J. Gilbert, and W. Radasky, "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid," Metatech Corp., Goleta, CA, Meta-R-320, Jan. 2010

Investigating Potential Grid Vulnerabilities



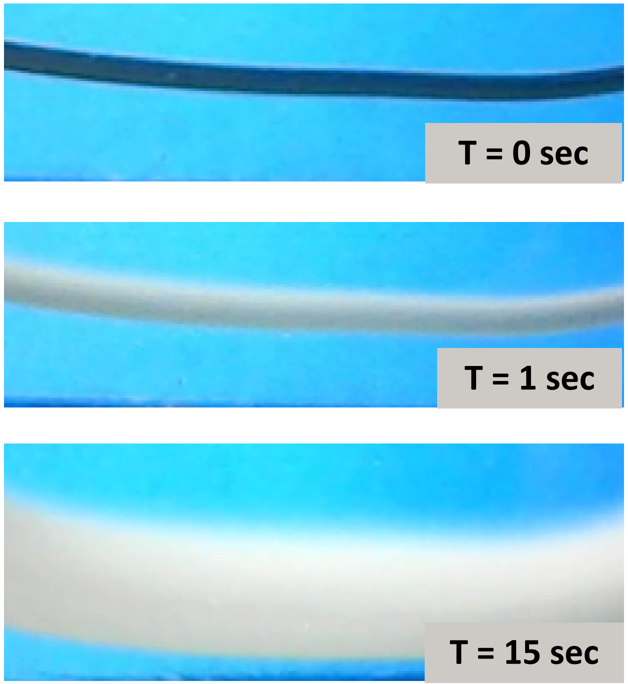
Investigating Potential Grid Vulnerabilities

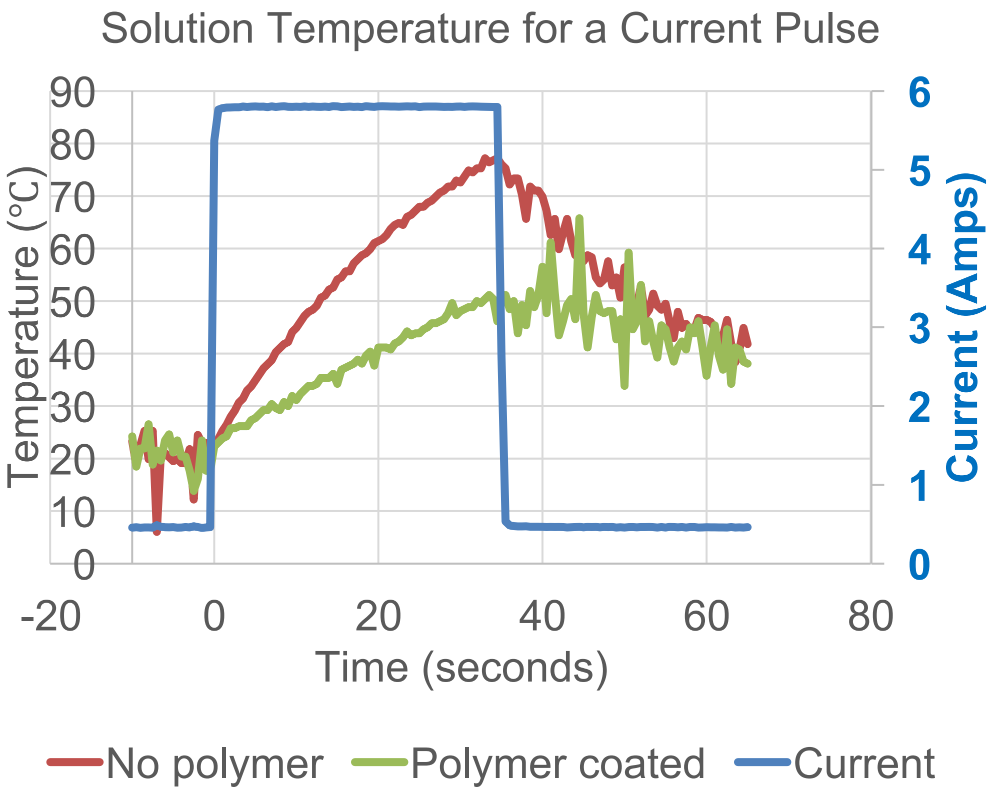




Mitigations Technologies as Applicable
above LCST: polymer condenses, improved thermal conduction in solid
Temperature
2 phases
LCST
1 phase
below LCST: poor thermal conduction in liquid phase
% Polymer
HPC Modeling
Xyce
TEM Wave Coupling
Electromagnetic Wave
High Freq. Transformer Modeling
Dielectric Withstand Testing
Setup RTS-96 System
Establish HEMP Scenarios
Couple HEMP Pulse to Grid Conductors
Find P(Fail | Vcouple)
E3 Voltage Collapse
Find Delay and Initialize E1 Failures
Run Dynamic Simulation
Enforce Security Constraints
Maximize Margins of Stability
Long Term System Recovery
Measure System Response
20%
35%

Transformer Oil Polymer Additive

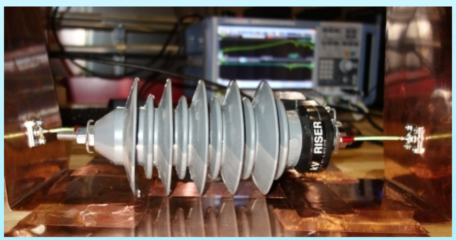


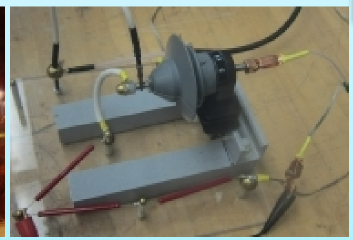


Example shown with an additive in an aqueous solution for initial proof of concept

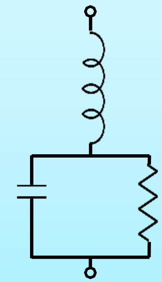
Roadmap of Arrester Work

Distribution Arrester Measurement:
- Bias dependent impedance
- I-V curve tracing
- Power frequency
- Pulse characterization

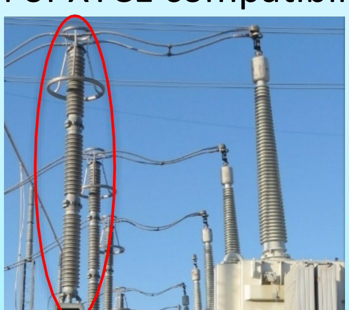




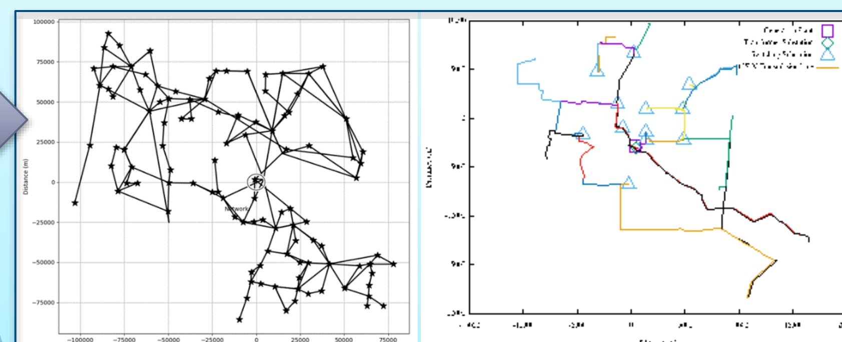
Scalable SPICE Circuit Model:
- Estimations from manufacturer data
- Critical HEMP response parameters
- Failure mode analysis



Transmission Arrester Model(s):
- Anticipated arrester response under HEMP with simple load
- Validation of XYCE compatibility



Integration into Coupling and Grid Simulations



Initial Substation Voltage Simulation (XYCE)

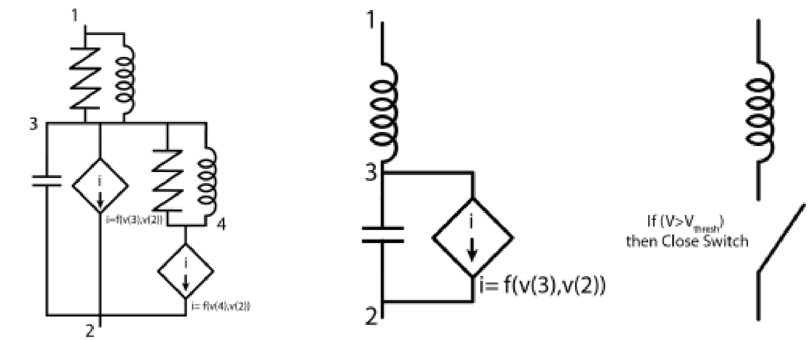
Preliminary results: little arrester clamping

Clamping response time requires more investigation

IEEE Working Group

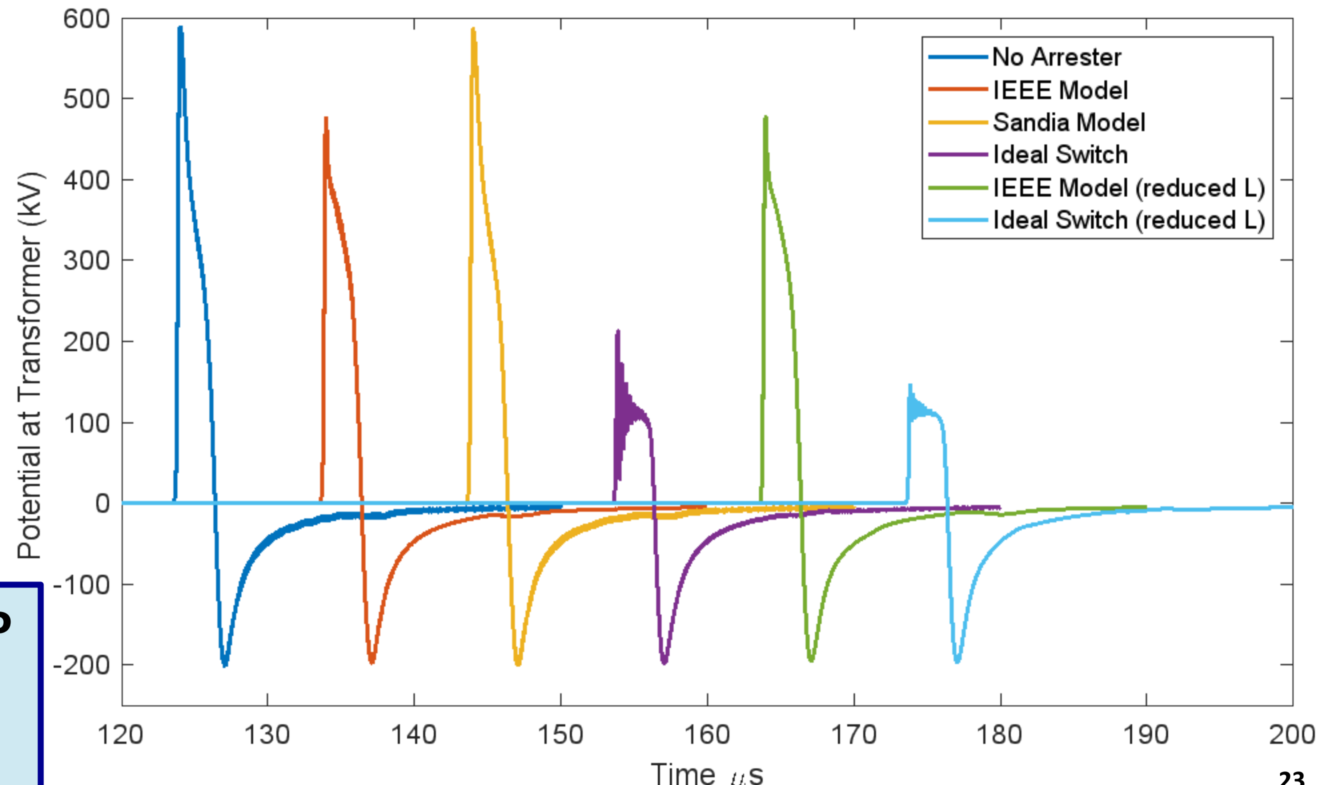
Sandia

Ideal



Reduced L:

- Lead: 1.87 nH
  - Order of magnitude
- Pedestal: 0.74 µH
  - Coaxial length approximation



There is a need for HEMP arresters and parasitic inductance handling.

Coupling Physics of Interest

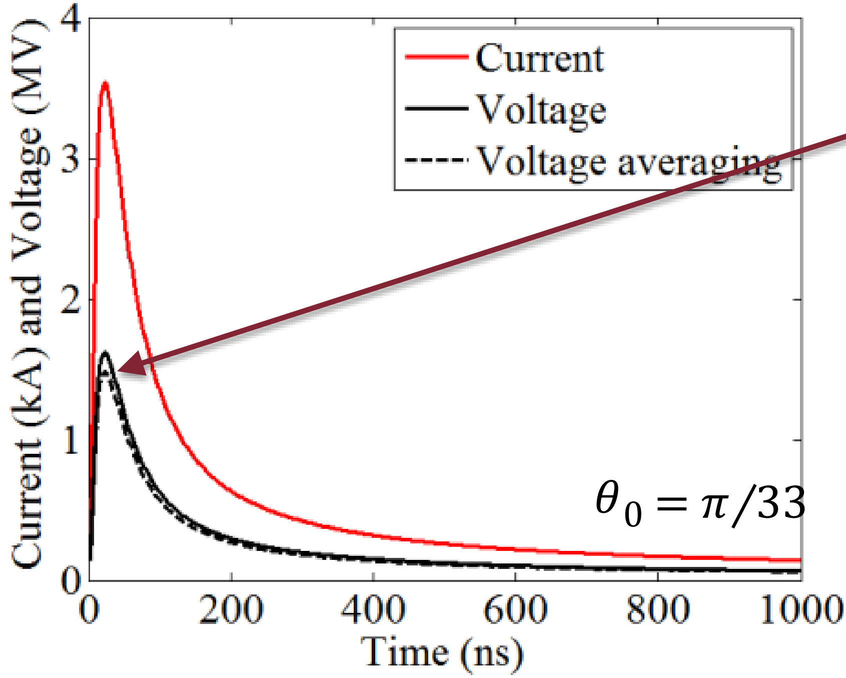
- Single line (equivalent conductor)
- Multiple lines (3-phase systems)
- Substation transition
- Tower impact
- Corona damping
- Instrumentation cable coupling
- Shield wire impact
- Line sag
- Insulator flashover/breakdown
- Substation meshed ground modeling
- …

Investigated Work (Single line, Multiple lines, Substation transition)

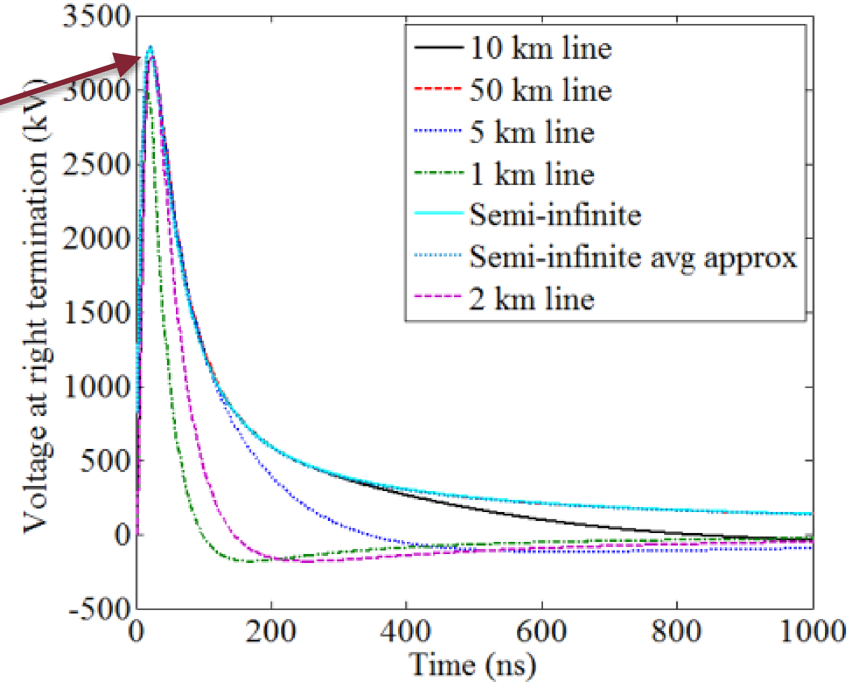
Ongoing or Future Work (Tower impact, Corona damping, Instrumentation cable coupling)

EMP Coupling to Transmission Lines

IEC-61000-2-9 EMP Waveform Coupling Study



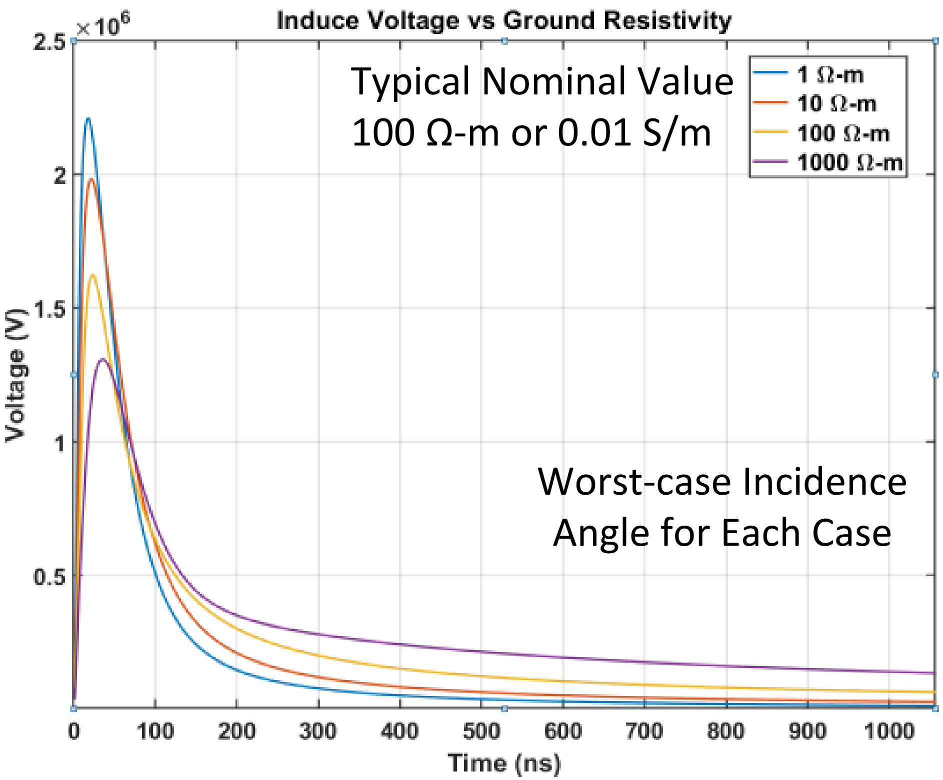
Matched Impedance Termination

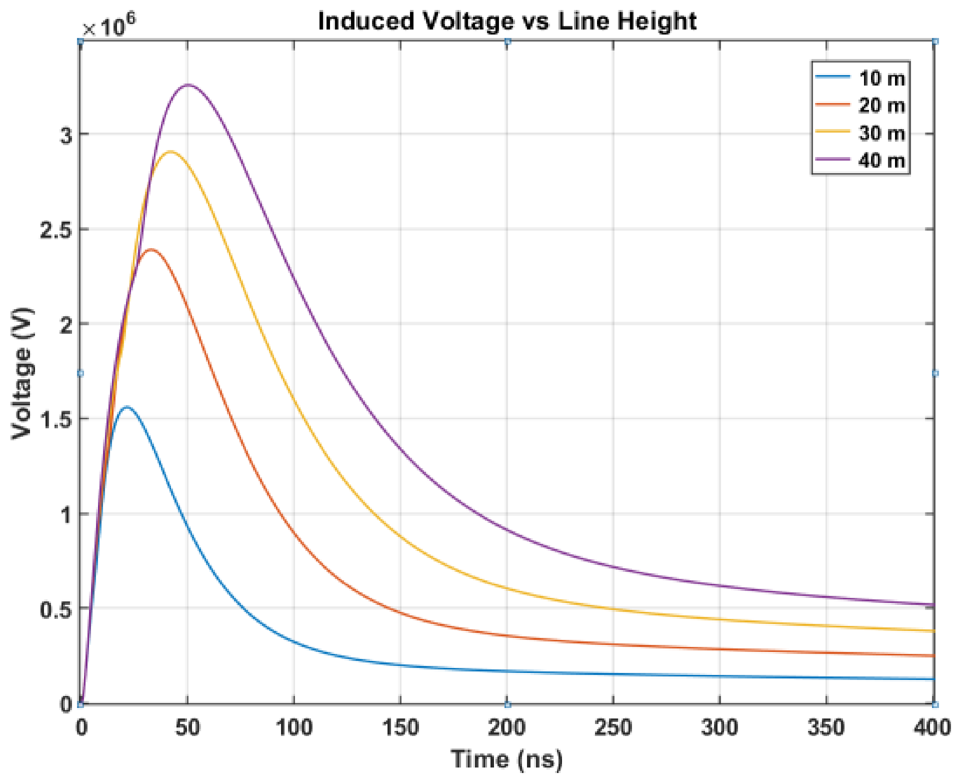


Open Termination

1. Effective coupling length on the order of several km
2. Terminating Impedance has a large effect on coupled voltages

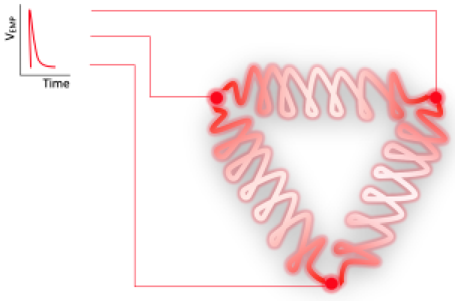
Coupling Sensitivity Analysis Results





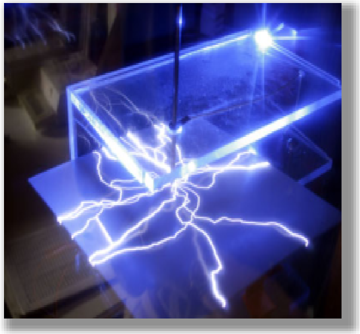
Coupling is sensitive to many variables, which are often not precisely known

Finding Risk of Dielectric Failure to HV Transformers Caused by HEMP

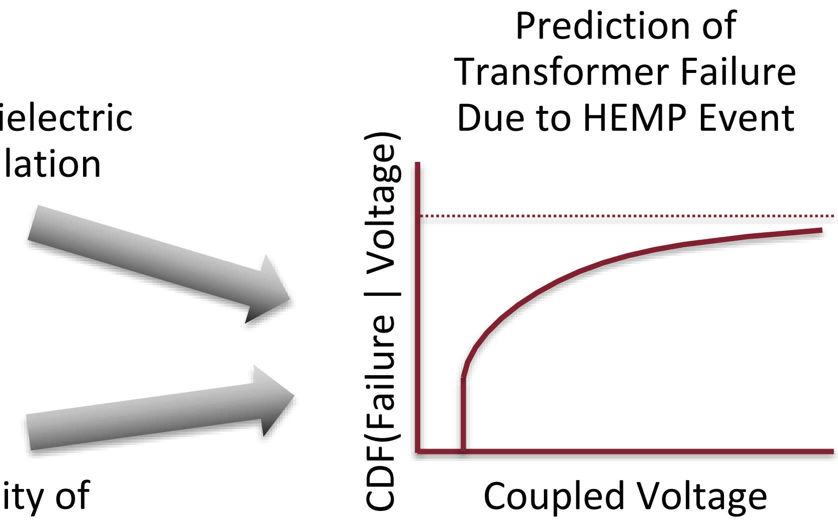


1. Develop High Frequency Winding Model, then Find Winding Voltage Due to HEMP

2. ABB will Calculate Dielectric Stress on Winding Insulation

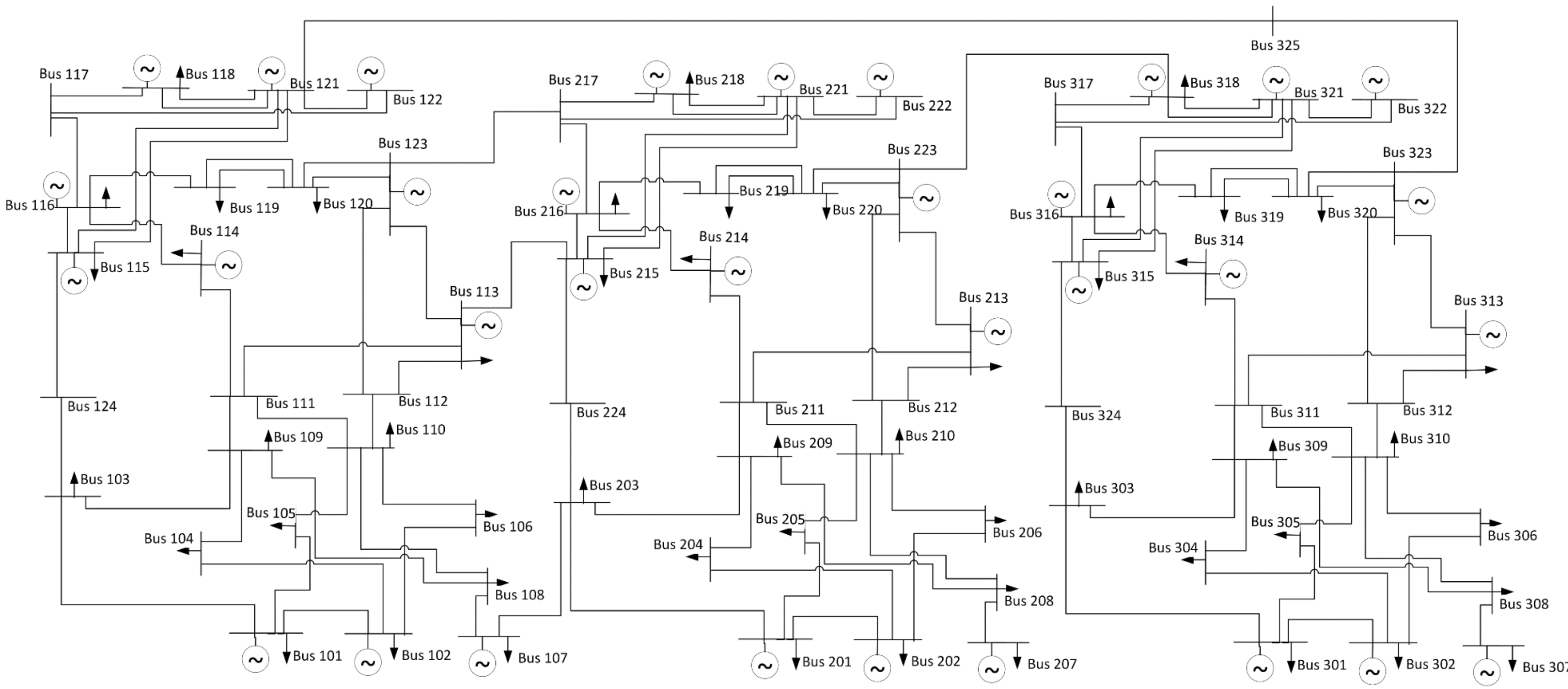


3. Test to find Probability of Dielectric Failure of Paper-Oil Insulation

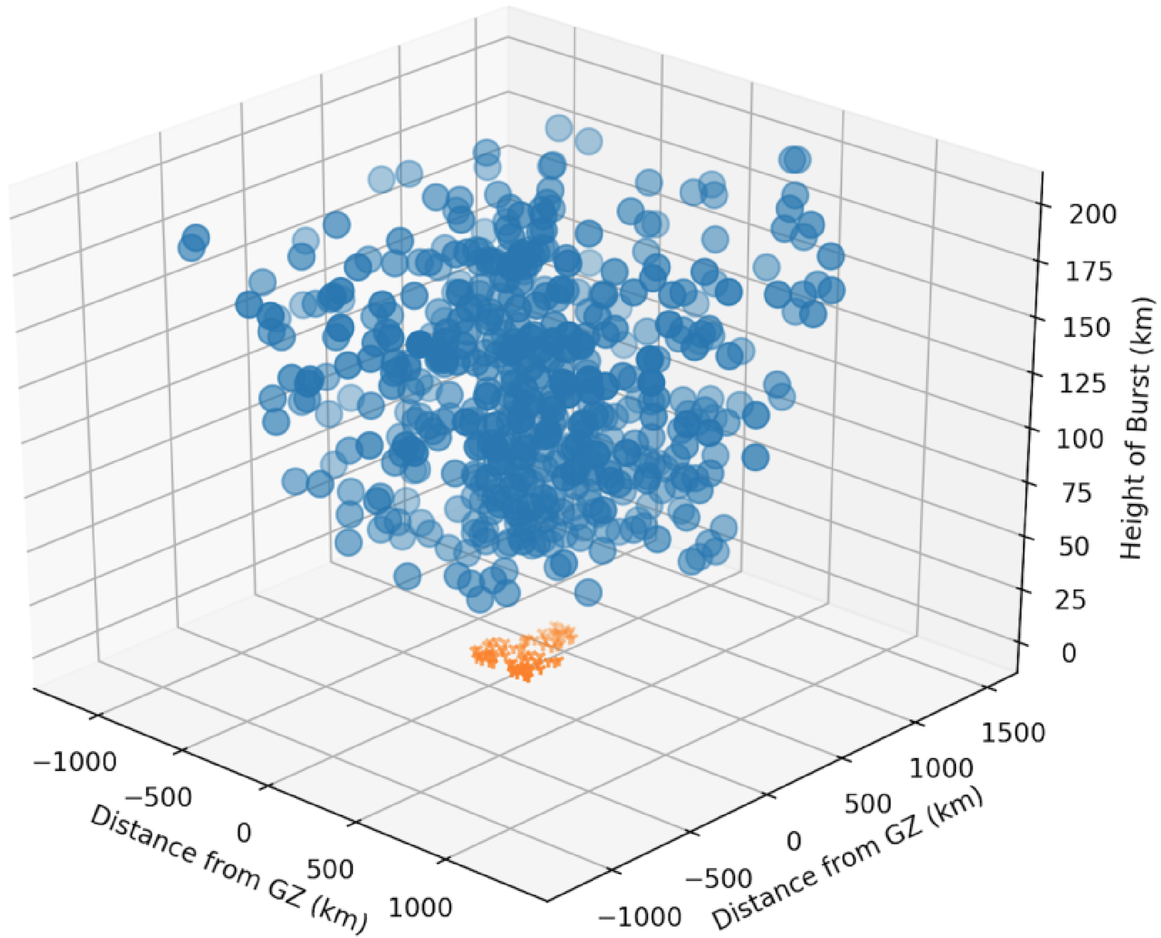


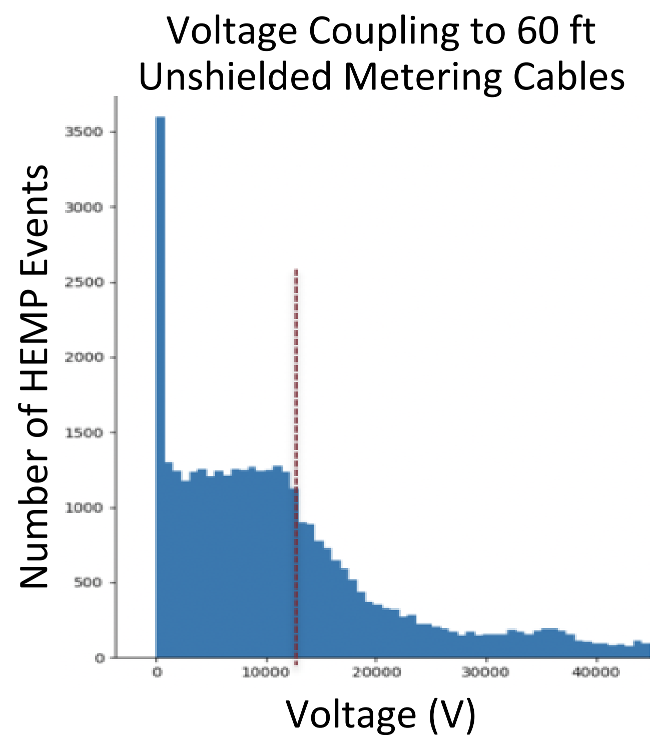
IEEE RTS-96 Grid System
Purpose: Identify System Effects

- Used by the NERC cascading outage study team
- Provides a point of comparison with published study results
- Shows the combined system effects expected from E1 and E3



HEMP Events above the RTS-96 Grid Model and Coupled Voltages



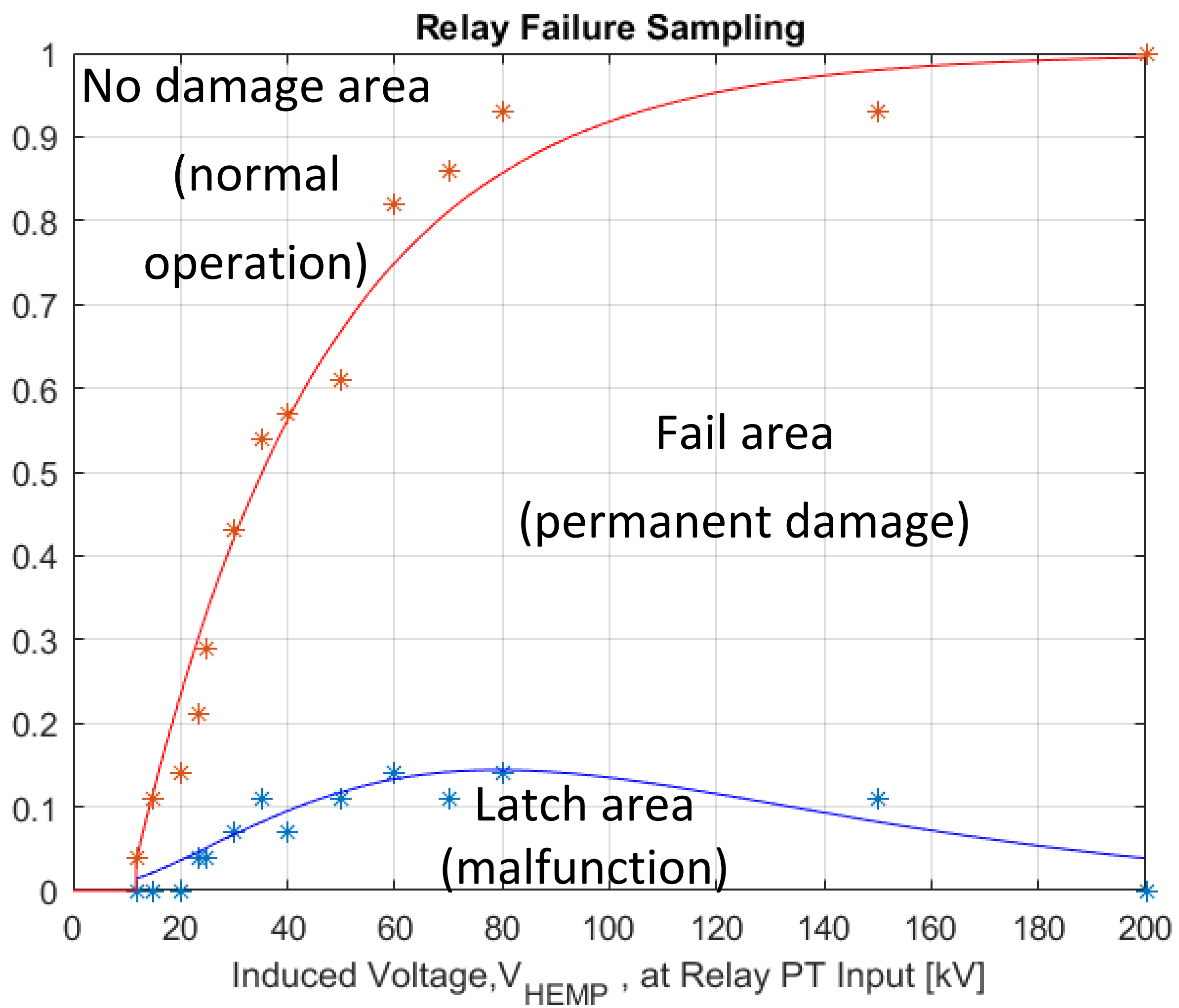


Relay Failure from Terminal Voltage

Relay failures caused by the induced voltage from a HEMP at the relay's input terminal

Data from recently released EPRI report and DTRA report

With more data, similar figures will be made for other components



Outcomes at the End of the Project

- Modeling Methodologies That Will:
  - Identify Failure Probabilities for Key Components
  - Calculate Voltage Stresses Inside Large Power Transformers
  - Incorporate E1 and E3 Failures into Dynamic System Simulations
    - Broadly Identify System Response to a HEMP
    - Identify Key System Vulnerabilities
- Critical Test Results
  - Impedance Testing for PTs and Power Transformers
  - Probabilistic Dielectric Withstand Tests for Paper-Oil
  - Combined Test-Analytic E1 Vulnerability Assessments for Large Power Transformers
  - Limited Component Testing for E1
- New Technologies
  - LCST Polymer Oil Additives for Thermal Management of Transformers
  - EMP Sub-Nanosecond Surge Arrestors
- New Analytic Methods
  - Methods to Calculate EMP Coupling, Shielding, and Shield Grounding Effectiveness
  - Methods to Apply Limited Test Results Across Broad Populations

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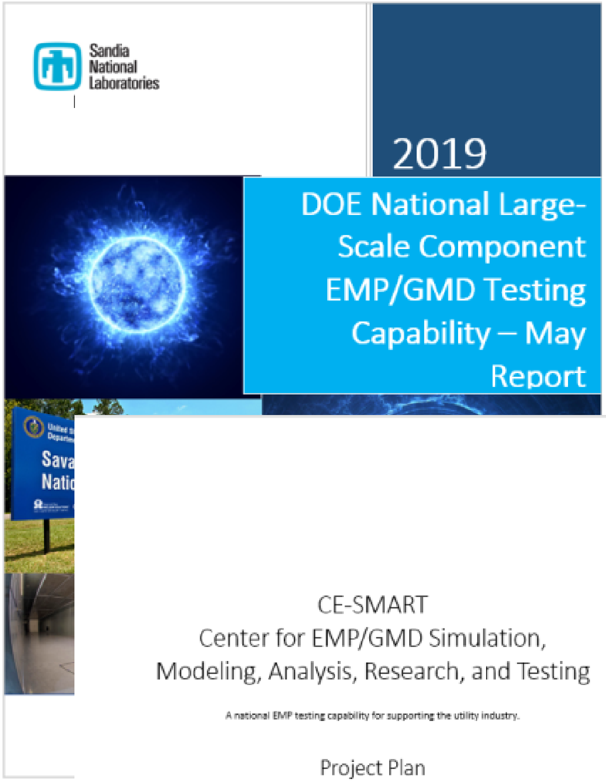
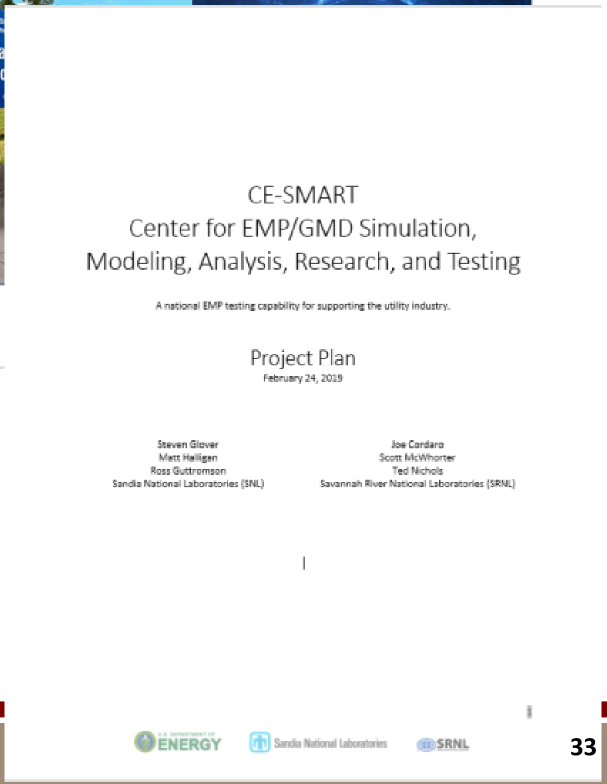
  - Electromagnetic Pulse (EMP) history
- EMP Laboratory Directed Research and Development (LDRD) Project Overview
  - Research thrust areas
  - Scope of research and analysis flow
  - Technology development and coupling results
  - Grid modeling approach
- **Center for EMP/GMD Simulation, Modeling, Analysis, Research, and Testing (CE-SMART) Project Overview**
  - Background
  - Executive order
  - Project structure
  - Next steps and summary

CE-SMART Project Background

- CE-SMART = Center for EMP/GMD Simulation, Modeling, Analysis, Research, and Testing
- Customer: Department of Energy, Office of Cyber Security, Energy Security, and Emergency Response (CESER)
- Initiated in FY19
- Objectives
  - Develop national capability to inform industry on electric grid hardness to EMP and GMD events
  - Create and implement solutions for grid hardening
- Differentiating factors
  - Development of integrated simulation, modeling, analysis, and testing capabilities
  - Large-scale testing
  - System-level modeling




CE-SMART
Center for EMP/GMD Simulation, Modeling, Analysis, Research, and Testing

A national EMP testing capability for supporting the utility industry.

Project Plan
February 24, 2019

Steven Glover
Matt Halligen
Ross Guttromson
Sandia National Laboratories (SNL)

Joe Cordaro
Scott McWhorter
Ted Nichols
Savannah River National Laboratories (SRNL)

ENERGY Sandia National Laboratories SRNL

Executive Order on EMP

- Issued 3/26/19
- Defines actions to increase EMP resilience
- Agencies with actions
  - Department of Commerce
  - Department of Defense
  - Department of Energy
  - Department of Homeland Security
  - Department of the Interior
  - Department of State

Executive Order on Coordinating National Resilience to Electromagnetic Pulses

INFRASTRUCTURE & TECHNOLOGY

Issued on: March 26, 2019

- SHARE:

ALL NEWS

By the authority vested in me as President by the Constitution and the laws of the United States of America, it is hereby ordered as follows:

Section 1. Purpose. An electromagnetic pulse (EMP) has the potential to disrupt, degrade, and damage technology and critical infrastructure systems. Human-made or naturally occurring EMPs can affect large geographic areas, disrupting elements critical to the Nation's security and economic prosperity, and could adversely affect global commerce and stability. The Federal Government must foster sustainable, efficient, and cost-effective approaches to improving the Nation's resilience to the effects of EMPs.

Sec. 2. Definitions. As used in this order:

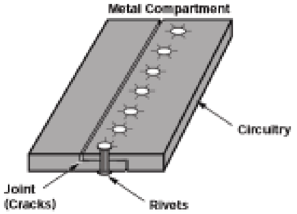
(a) "Critical infrastructure" means systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters.

(b) "Electromagnetic pulse" is a burst of electromagnetic energy. EMPs have the potential to negatively affect technology systems on Earth and in space. A high-altitude EMP (HEMP) is a type of human-made EMP that occurs when a nuclear device is detonated at approximately 40 kilometers or more above the surface of Earth. A geomagnetic disturbance (GMD) is a type of natural EMP driven by a temporary disturbance of Earth's magnetic field resulting from interactions with solar eruptions. Both HEMPs and GMDs can affect large geographic areas.

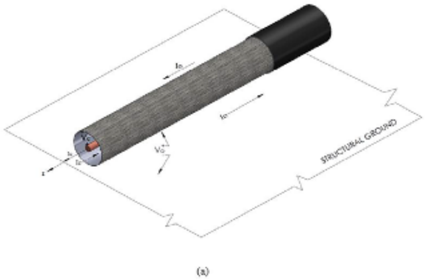
(c) "National Critical Functions" means the functions of government and the private sector so vital to the United States that their disruption, corruption, or dysfunction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof.

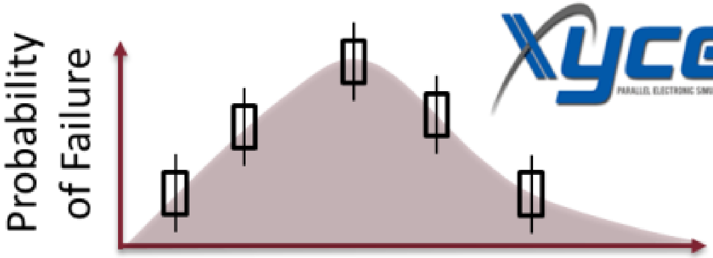
Advancements and Gaps in Grid EMP Response

- Advancements are being made in:
  - Analysis
  - Modeling and simulation
  - Experimental capabilities and validation
- Gaps remaining:
  - Component and system vulnerability knowledge
  - Utility access to appropriate validation platforms



Coupling Pathways



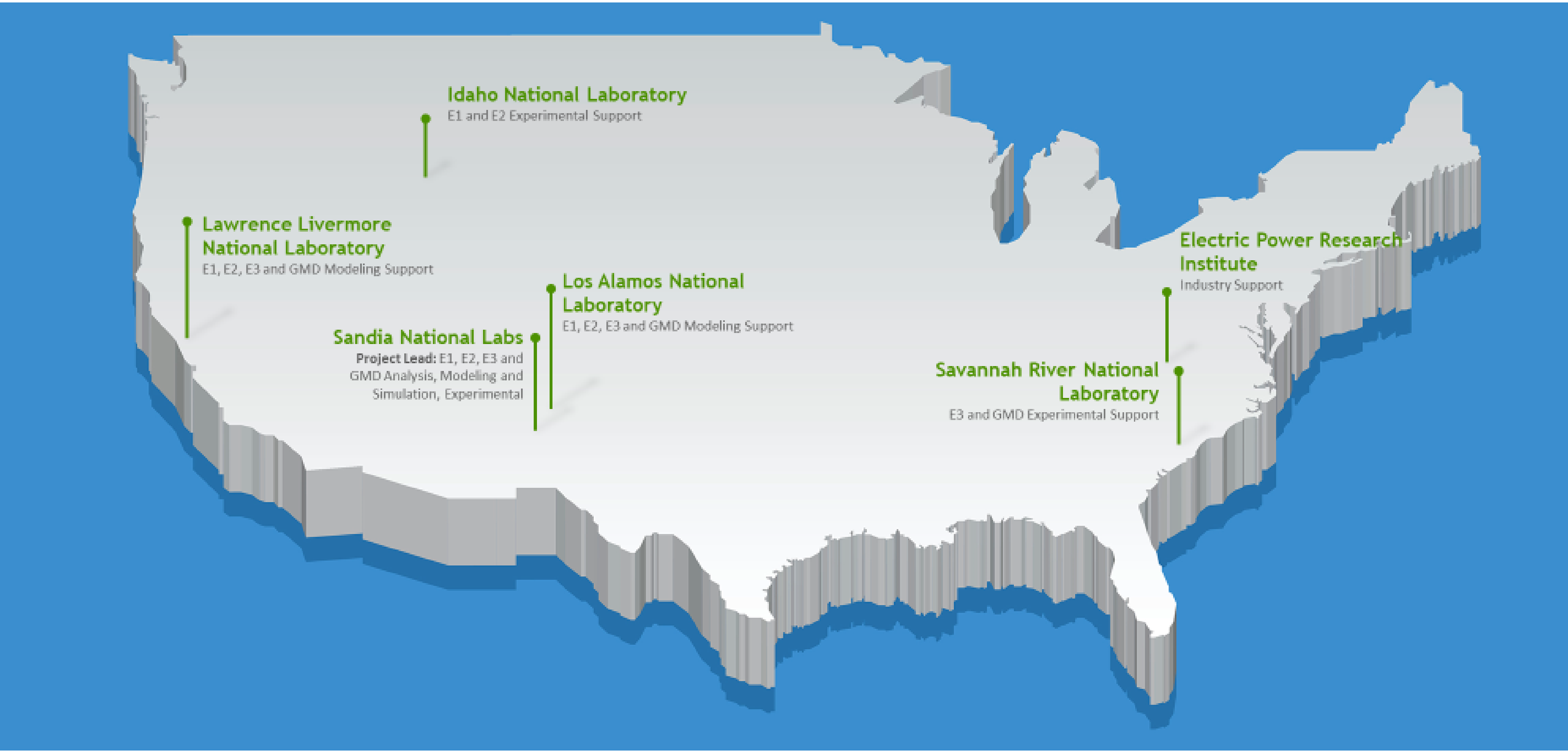


Program Leadership

Funding Agency	Department of Energy
Program Lead	Sandia National Laboratories
Team Members	Savannah River National Laboratories
	Electric Power Research Institute

Other team members will be added as we move forward

Multiple National Laboratories will be Leveraged



Contacts will be made as the structure matures

CE-SMART Path to EMP Hardening of the Grid

Intelligence community

Threat assessment

LANL

LLNL

SNL

SRNL

Others?

Define processes and methods

Perform global (system) analysis

Consult to FERC, NERC, and industry

Vulnerability assessments

Testing: classified, specialized, large-scale, initial

Develop mitigation strategies

Oversee/lead industry testing

Track resiliency evolution of the grid

Honest broker for new technology evaluation

R&D

Trilab results

IP management

Establish standards

Create classification guides

Knowledge transfer to industry, DoD, DHS, FERC, NERC, and utilities

Increased resiliency to EMP

Current Tasking for CE-SMART

- Develop CE-SMART strategic plan
  - Multi-year plan to execute DOE activities per the executive order
  - To include initiatives and projects for energy sector consideration
  - Deliverable: strategic plan (12/30/19)
- Plan to address EMP standards
  - Review existing EMP standards
  - Develop/update benchmarks describing EMPs
  - Deliverable: EMP standards analysis report (2/15/19)
- Develop and implement EMP pilot program
  - Demonstrate cost and effectiveness of EMP mitigation
  - Application: blackstart and cranking path including generation
  - Deliverables
    - Develop pilot program plan (3/30/20)
    - Execute pilot program plan (9/30/20)

Summary

- Working to mitigate risk to EMP and GMD with info and technologies to industry
- Impact of EMP and GMD on the electric grid at the national level is:
  - Recognized as important
  - Driving efforts to mitigate risks
- Sandia has a long history of working with EMP
  - Existing knowledge and capabilities leveraged
  - R&D with Grand Challenge LDRDs and capability development
- Collaboration with other government agencies and industry critical to meet national grid resiliency needs

Thank You

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Backup Slides

Extended SNL History with EMP

- Founding as LANL Z Division (1945), became Sandia Laboratory (1948)
- 1962 Starfish Burst – Honolulu Streetlight Incident Analysis (SAND Report 1989)
- Fault Tree Methodology used for Power Plants EMP Effects (1982)
- EMP/EM penetration into enclosures and through cable shielding (1994-present)
- Congressional EMP Commission measurement support (2003-2004)
- NRC Sponsored Watts Bar and Fermi-II Nuclear Power Plants EMP/HPM Studies (2008-2010)
- North American Air Defense (NORAD) EMP Protected Shield-Room Installation (2009-2010)

Recent SNL History with EMP

- DoD Sponsored Urban EMP Infrastructure Response Modeling (2012-2016)
- Fast simulation tool suite for EMP coupling to above ground and buried cable systems for DOE (2013-present)
- DoD-DOE Collaboration on EMP Grid Response Modeling Capabilities (2015-2017)
- Tri-lab EMP reports (2017, 2018)
- **EMP-Resilient Electric Grid for National Security Grand Challenge LDRD (2018-2020)**
- **Center for EMP/GMD Simulation, Modeling, Analysis, Research, and Testing (CE-SMART) (2018-present)**

EMP LDRD Acknowledgements

Sandia Researchers

- Alfred Baughman
- Tyler Bowman
- Salvo Campione
- Megan Daily
- John Eddy
- Matt Halligan
- Matt Hoffman
- Dale Huber
- Todd Hendrickson
- Rodrigo Llanes
- Olga Lavrova
- Brian Pierre
- Lee Rashkin
- Luis San Martin
- Rich Schiek
- James Taylor
- Larry Warne
- April Zwernenman
- Brian Arguello

External Partners

- ABB
- Public Service Co. of NM (PNM)
- National Grid
- ITC
- Electric Power Research Institute
- Texas A&M
- University of NM
- Los Alamos and Lawrence Livermore National Laboratories
- Department of Energy
- Federal Energy Regulatory Agency
- Defense Threat Reduction Agency

SRNL Background

- General information
  - 310 mi^2 DOE protected and isolated site
  - 5 operating nuclear reactors
  - 2 nuclear reprocessing facilities
  - 93 mi of 115 kV transmission line
  - Operated jointly by SRNS and Dominion Energy
  - 230 kV interconnection to GA Power
  - State of the art 25 MW biomass co-generation plant
- C Area
  - 24 MVA available power from 2 in area substations
  - Additional power sources available
  - Virtually unlimited space for testing large power substation components