

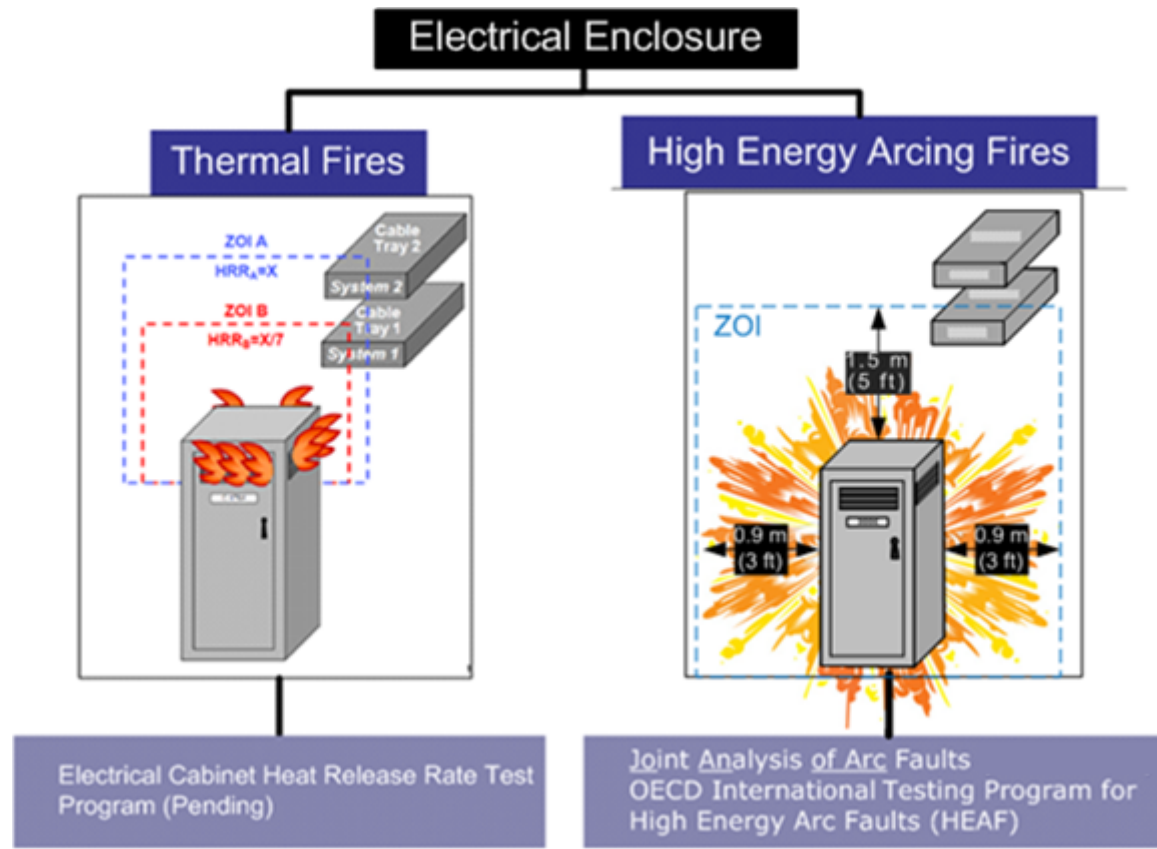
High Energy Arcing Faults (HEAF) Hazard Modeling

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July 24, 2019

Purpose

- Provide overview of modeling
 - History
 - Types
 - Existing models
 - Comparisons to measurement

Categories of Electrical Enclosure *Failure Mode - Review*



Operating Experience

San Onofre Nuclear Generating Station, 2001

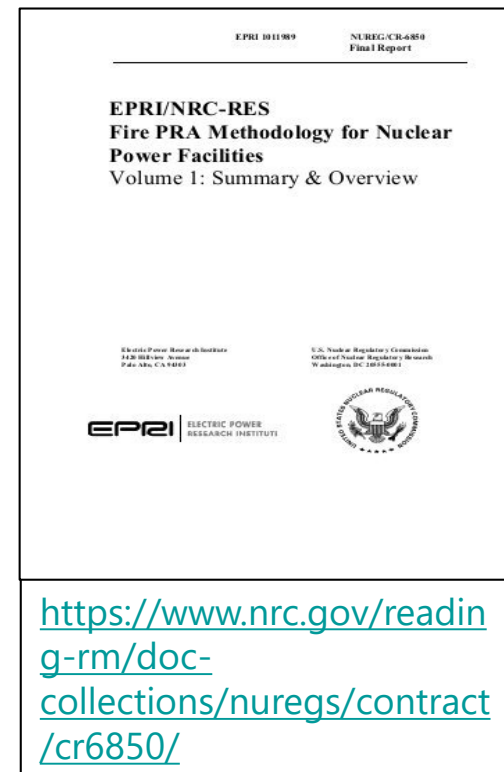
- Highlighted HEAF hazard
- NRC INFORMATION NOTICE 2002-27
 - RECENT FIRES AT COMMERCIAL NUCLEAR POWER PLANTS IN THE UNITED STATES
 - <https://www.nrc.gov/docs/ML0226/ML022630147.pdf>



Fire PRA Methodology

NUREG/CR-6850 EPRI 1011989

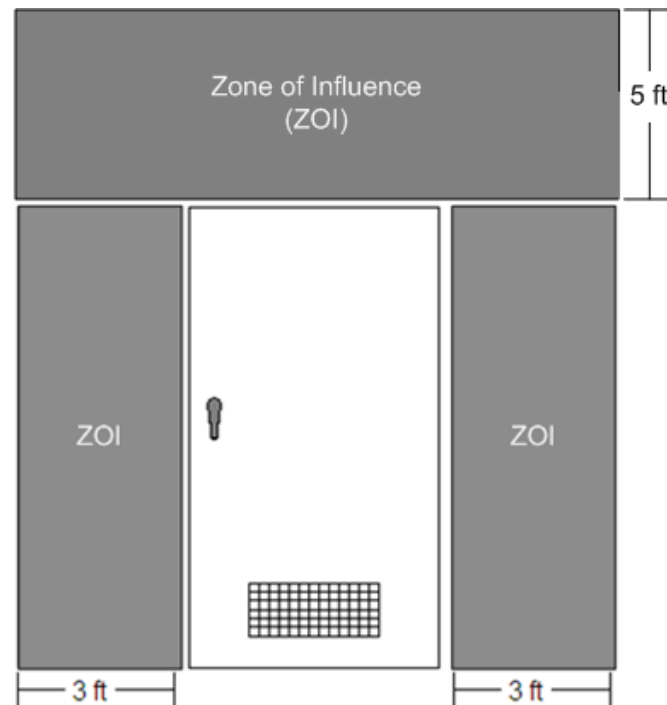
- NUREG/CR 6850 forms the basis for nuclear power plant (NPP) Fire PRA's
 - Published 2005
- This EPRI/NRC working group was the first to explicitly model HEAF events as part of a fire PRA
 - The need was identified as part of accident investigation efforts for the development of 6850 & NRC's assessment of energetic faults from 1986-2001
 - (ADAMS Accession No. [ML021290364](#))
 - Timely OpE- San Onofre 2/3/2001



Current Methodology

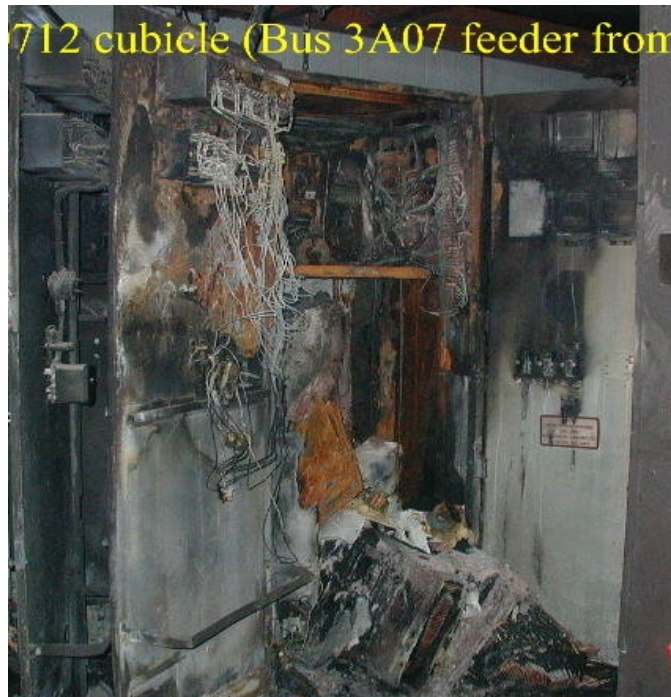
Electrical Enclosures

- NUREG/CR-6850, Appendix M (2005)
- Zone of Influence (ZOI) Method largely based on one well documented fire event at San Onofre in 2001
- Methodology developed as an expert elicitation
 - Observational data and OpE information only
 - No test data available
 - Currently this model has been used to support NFPA 805 transitions

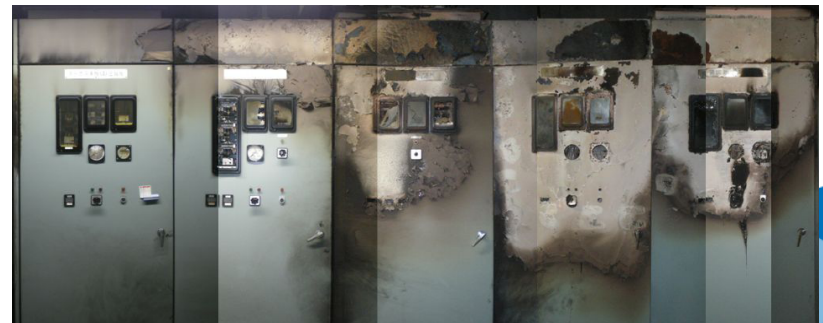
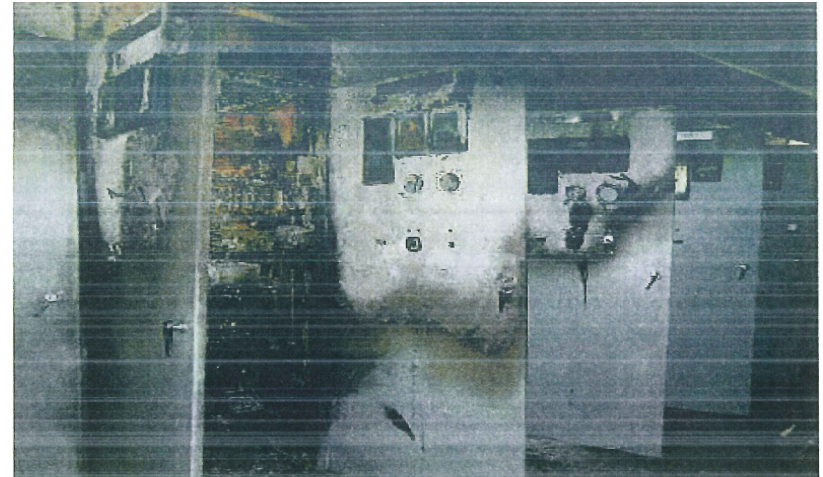


HEAF OpE

Electrical Enclosure



San Onofre; 2001

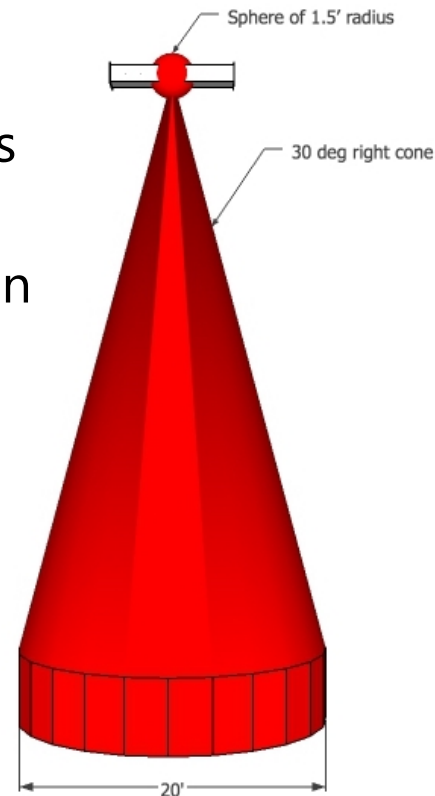


Onagawa; 2011

Current Methodology

Bus Ducts

- NUREG/CR-6850, Supplement 1
- Bus duct guidance for high energy arcing faults (FAQ 07-0035)
- Methodology developed as an expert elicitation
 - Observational data and OpE information only
 - No test data available
 - Currently this model has been used to support NFPA 805 transitions



HEAF OpE

Bus Duct



Diablo Canyon Bus Duct (OpE)
2000



Bus Duct Testing
2016



Columbia Bus Duct (OpE)
2009

Conceptual Modeling Approaches

Modeling Approach

- Bounding (Current models)
 - Enclosure, bus ducts
- Bounding by Categories
 - By power, energy, voltage, fault current, protection scheme, material, safety class
- Dynamic ZOI
 - Scenario dependent source
 - Target fragility

$$E = kVI\left(\frac{t}{D^p}\right)$$

$$E = k_1 \cdot t \cdot \left(\frac{k_2}{D}\right)^x \cdot 10^{[k_3 + k_4 \cdot \log(I) + k_5 \cdot G]}$$

Bounding ZOI (Current Model)

- Assumes worst case damage for all HEAF
 - i.e., one size fits all
 - Damage and ignition of components within ZOI
 - Peak HRR
- Least amount of information needed to determine ZOI
- Least realistic for majority of cases
- Simple **to apply**
- Lowest cost



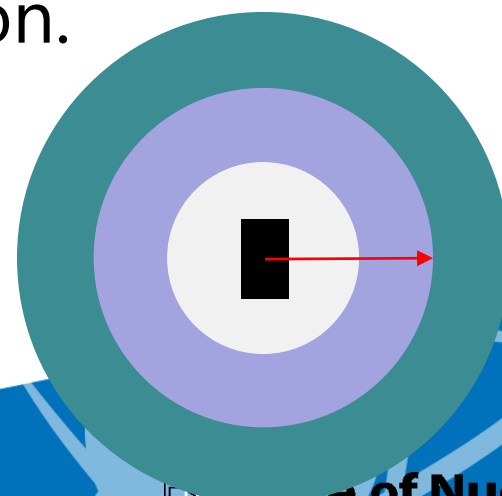
Refined Bounding ZOI

- Subdivides equipment by HEAF damaged potential
 - Equipment type
 - Energy/Power potential
 - Protection scheme
 - Size, Material, Design, etc.
- More realistic
- Requires more information to apply
- More costly for development and application



Dynamic ZOI

- Requires detailed information on power system
- Correlation from experiments and theory to model source term and incident flux as a function of distance
- Requires knowledge of fire PRA target fragility to high heat flux short duration.
- Potential to provide most realistic results
- Complex
- Most costly



Modeling Approach

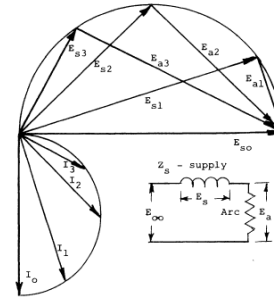
Status

- No approach has been excluded
- Understand and evaluation existing and new hazard models
- Needs to consider development and application efficiencies along with level of realism in a holistically manner to make informed decision on approach
- NRC/EPRI working group advancing "PRA modeling" methodology

Overview of Existing Models

Theoretical

Lee Model



- Simple geometric configuration
 - arc modeled as sphere
- Heat transfer to predict distance where threshold is exceeded
- Used available research on human skin / clothing fragility (Stoll / Artz)
- Conservative due to maximum arc power assumption
- Used in IEEE 1584-2002 for $> 15\text{kV}$ applications

R. Lee, *The Other Electrical Hazard: Electric Arc Blast Burns*, 1982

Theoretical

Lee's Method

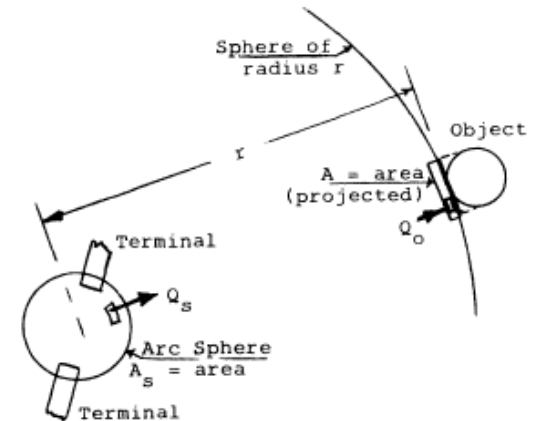


Fig. 1. Illustration of arc source and heat-receiving object.

- Output

- IE, incident energy (J/cm^2)

- Inputs

- V, system voltage (kV)
- t, arcing time (seconds)
- I_{bfr} , 3 phase bolted fault current
- D, distance from arc point

ASTM slug

T-cap. slug

KEMA Daq

Physical Measurement

R. Lee, *The Other Electrical Hazard: Electric Arc Blast Burns*, 1982



Semi-Empirical

Wilkins-Allison-Lang Method

- Output

- IE, incident energy

ASTM slug

T-cap. slug

- Input

- V_{LL} , line-line voltage

- V , system voltage

- V_{arc} , arc voltage

- I_{arc} , arc current

- t , arcing time

- D , distance from arc point

- a , enclosure dimension

- g , gap

- V_e , electrode voltage

KEMA Daq

Physical Measurement

Literature

R. Wilkins, M. Allison, M. Lang, *Improved Method for Arc Flash Hazard Analysis*, 2004

Semi-empirical

Gammon Simplified

- Output

- IE, incident energy

ASTM slug

T-cap. slug

- Input

- MVA_{sc}, short-circuit MVA

- t, arcing time

- D, distance from arc point

- X, configuration factor (IEEE)

- $IE_{ratio_{UB}}$, Incident energy rate ratio upper bound
(configuration based 0.758 – 2.098)

KEMA Daq

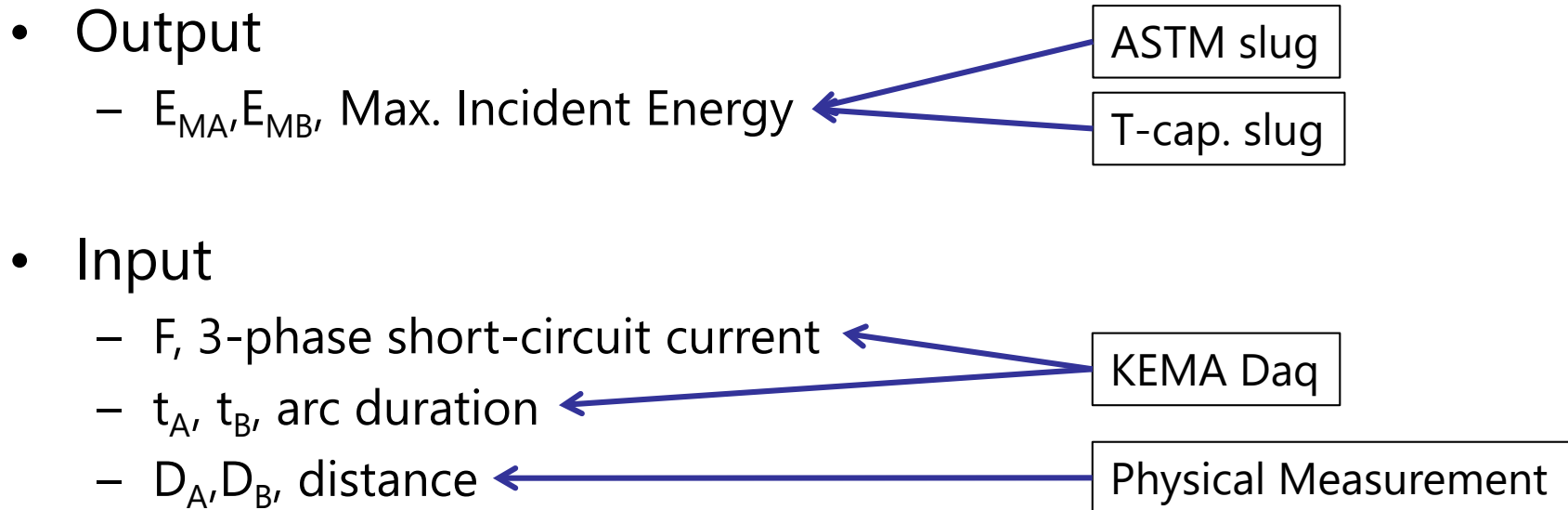
Physical Measurement

Literature

T. Gammon, J. Matthews, *The IEEE 1584-2002 Arc Modeling Debate and Simple Incident Energy Equations for Low-Voltage Systems*, 2006

Empirical – Statistical

Doughty – Neal – Floyd

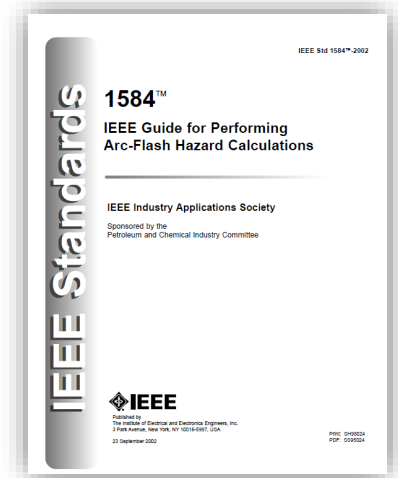


R. Doughty, T. Neal, H Floyd, *Predicting Incident Energy to Better Manage the Electric Arc Hazard on 600-V Power Distribution System*, 2000

Empirical - Statistical

IEEE 1584 - 2002

- Guide for performing arc flash calculations
- Model for incident energy calculations
- Empirically derived model from 300 tests
- Methodology focused on personal protection
 - Arc flash boundary is only applicable to human fragility
 - Arc fault current and incident energy are independent of target



IEEE 1584-2002, *Guide for Performing Arc-Flash Hazard Calculation*, 2002

Empirical - Statistical

IEEE 1584 - 2002

- Output

- IE, Incident Energy

ASTM slug

T-cap. slug

- Input

- V , system voltage

- I_a , arc current

- t , arc duration

- G , conductor gap

- D , distance

- x , distance exponent

- Configuration (open / box)

KEMA Daq

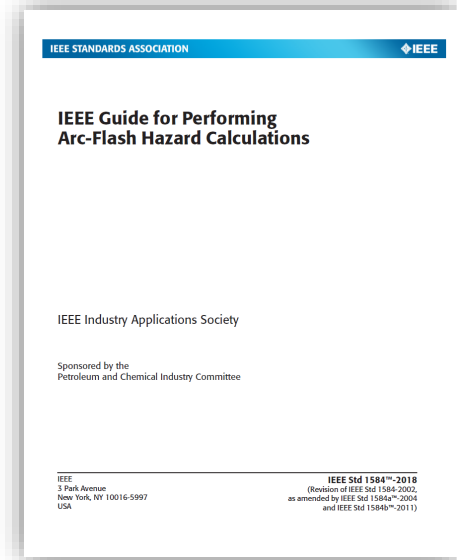
Physical Measurement

Literature

IEEE 1584-2002, *Guide for Performing Arc-Flash Hazard Calculation*, 2002

Empirical - Statistical

IEEE 1584 - 2018



IEEE 1584-2018, *Guide for Performing Arc-Flash Hazard Calculation*, 2018

- Guide for performing arc flash calculations
- Significantly changed from 2002 edition
- Model for incident energy calculations
- Empirically derived model from 2,160 tests
- Five configurations
 - VCB, VCBB, HCB, VOA, HOA



IEEE 1584 - 2018

Range of model

- System voltage: 208 to 15,000 Volts
- Frequency: 50 or 60 Hz
- Bolted fault current:
 - Low Voltage: 500 to 106,000 A
 - Med Voltage: 200 to 65,000 A
- Conductor Gaps:
 - Low Voltage: 0.25 to 3 inches
 - Med Voltage: 0.75 to 10 inches
- Target Distances: ≥ 12 inches
- Fault clearing time: no limit

Empirical – Statistical

IEEE 1584-2018

- Output

- IE, Incident Energy

ASTM slug

T-cap. slug

- Input

- I_{bfr} Bolted fault current

- V_{oc} System voltage

- T , Duration

- D , Distance

- G , Conductor gap

- Enclosure Dimensions

- Equip Configuration

KEMA Daq

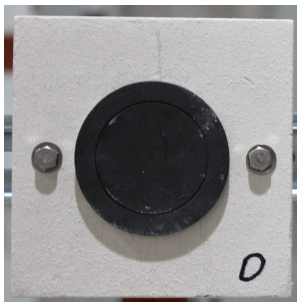
Physical Measurement

Literature

Model Comparison

IEEE 1584 – 2018 vs MV Alum

- ASTM slug calorimeter (copper)
 - Model overpredict max measured incident energy
 - Maximum overprediction : ~11x
 - 550 kJ/m² measured vs. 6,100 kJ/m² calculated
 - Minimum overprediction : ~2x
 - 3.4MJ/m² measured vs. 6.3MJ/m²
 - Note: 2 instruments damaged due to HEAF damage likely higher heat flux at damaged sensors and better agreement with model



Model Comparison

LEE vs MV Alum

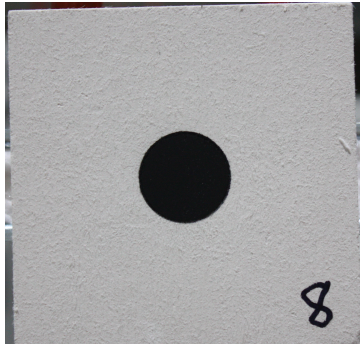
- ASTM slug calorimeter (copper)
 - Model overpredict max measured incident energy
 - Maximum overprediction : $\sim 17x$
 - 550 kJ/m^2 measured vs. $9,100 \text{ kJ/m}^2$ calculated
 - Minimum overprediction : $\sim 3x$
 - 3.4 MJ/m^2 measured vs. 9.4 MJ/m^2 calculated
 - Note: 2 instruments damaged due to HEAF damage likely higher heat flux at damaged sensors and better agreement with model



Model Comparison

IEEE 1584 – 2018 vs MV Alum

- T-cap slug calorimeter (tungsten)
 - Model overpredict max measured incident energy
 - Maximum overprediction : ~26x
 - 236 kJ/m² measured vs. 6,100 kJ/m² calculated
 - Minimum overprediction : agreement
 - 6.0MJ/m² measured vs. 6.3MJ/m²



Model Comparison

LEE vs MV Alum

- T-cap slug calorimeter (tungsten)
 - Model overpredict max measured incident energy
 - Maximum overprediction : ~39x
 - 236 kJ/m² measured vs. 9,100 kJ/m² calculated
 - Minimum overprediction : ~1.6x
 - 6.0MJ/m² measured vs. 9.4MJ/m²

Wrap-up

Existing Models

- Follow similar form
 - Inverse power relationship with distance to target
- Supporting test configurations not directly applicable
 - Open air or box w/opening
- Fragility different (human vs equipment)
- Existing models may be adapted to make representative and realistic.