High Energy Arcing Faults (HEAF) Hazard Modeling

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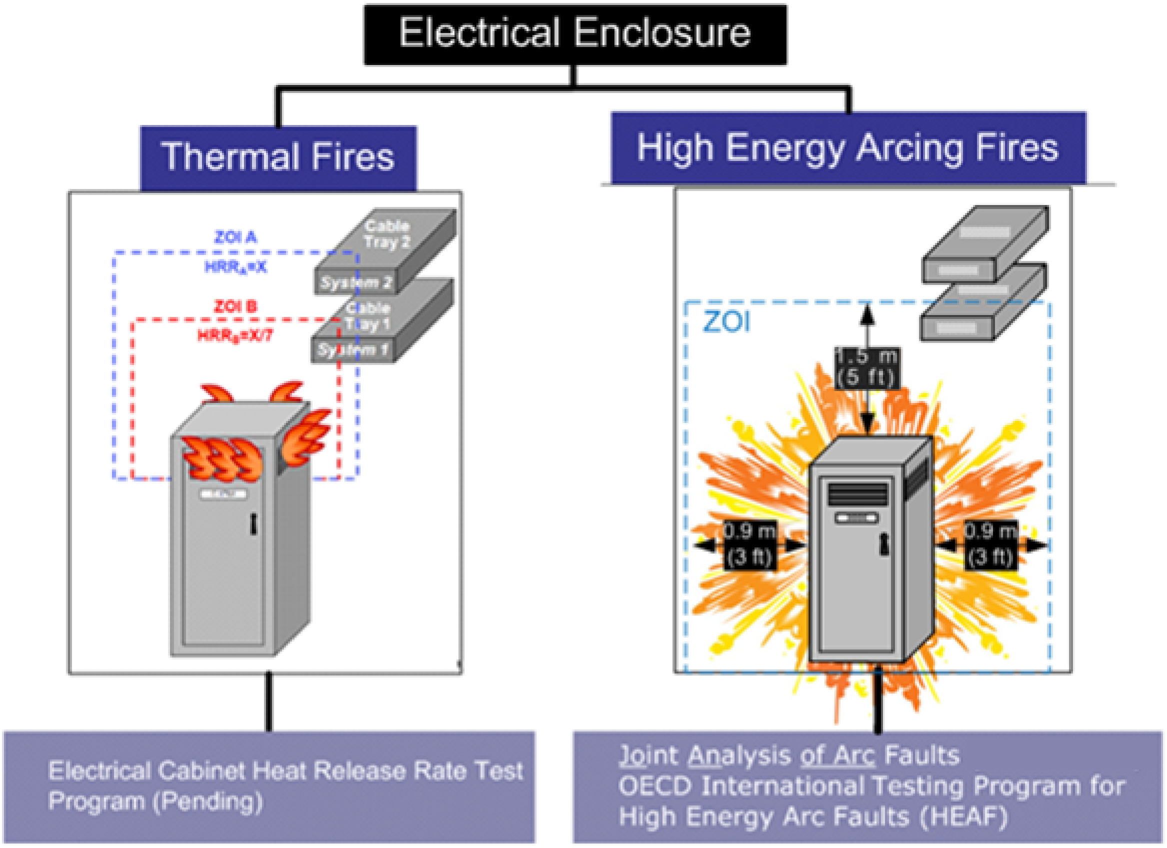
Purpose

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

Categories of Electrical Enclosure
Failure Mode - Review



Operating Experience

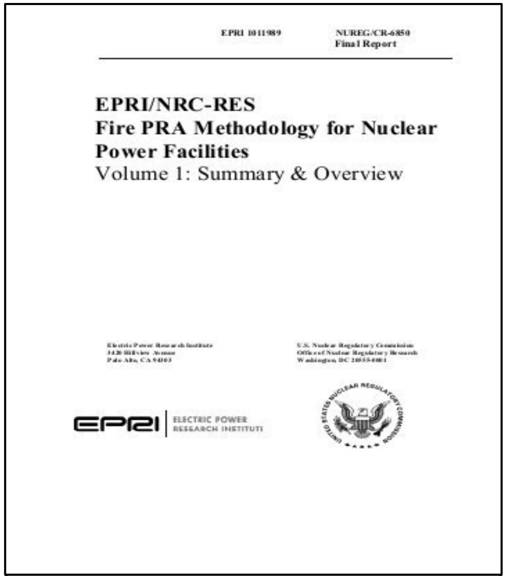
San Onofre Nuclear Generating Station, 2001

- 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


EPRI 1011989 NUREG/CR-6850 Final Report

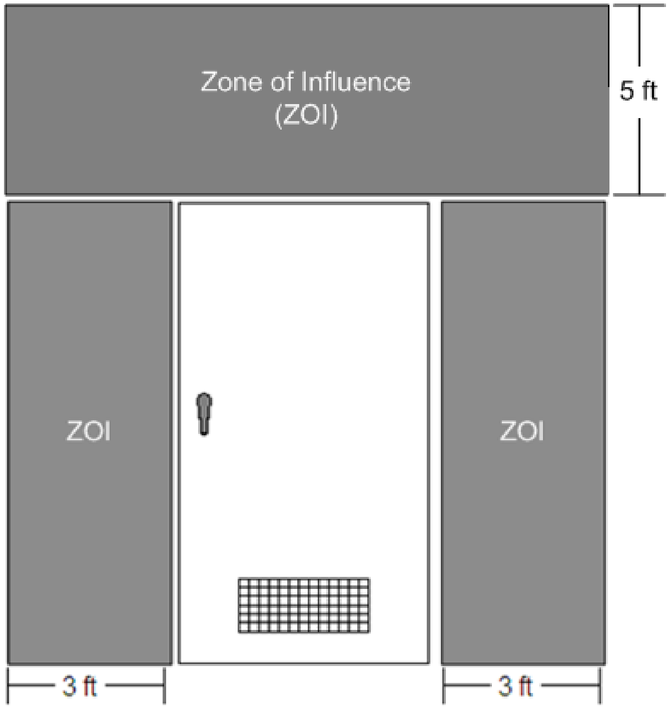
EPRI/NRC-RES
Fire PRA Methodology for Nuclear Power Facilities
Volume 1: Summary & Overview

https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/

Current Methodology

Electrical Enclosures

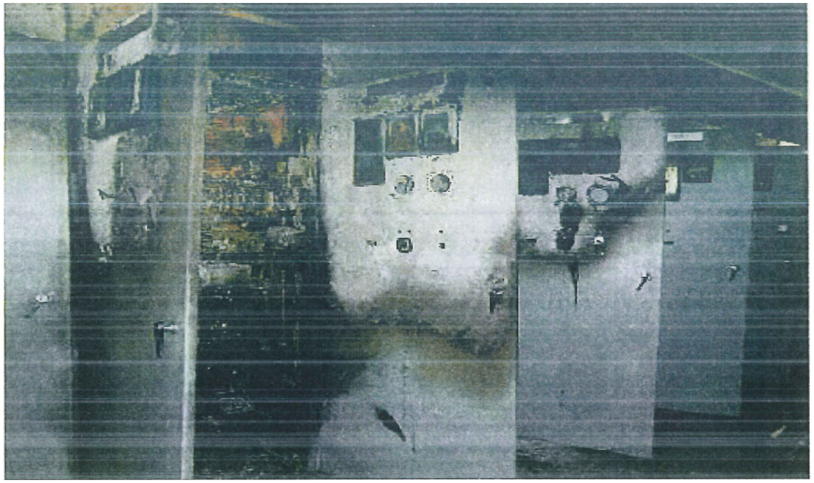
- NUREG/CR-6850, Appendix M (2005)
- Zone of Influence (ZOI) Method largely based on one well documented fire event at San Onofre in 2001
- Methodology developed as an expert elicitation
  - Observational data and OpE information only
  - No test data available
  - Currently this model has been used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



HEAF OpE

Electrical Enclosure

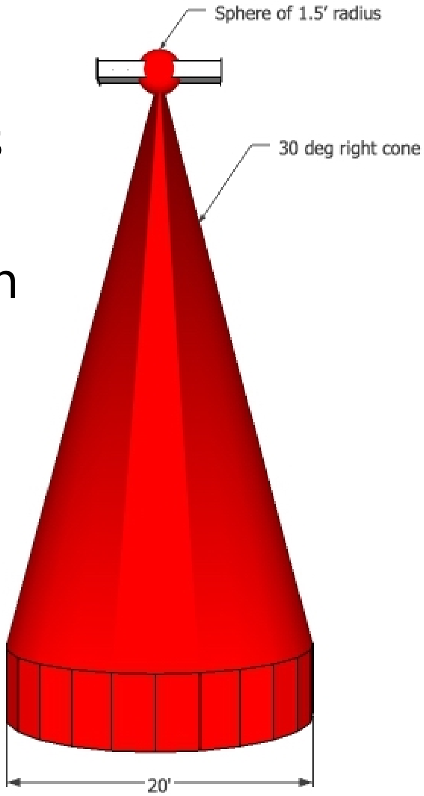
San Onofre; 2001



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



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HEAF OpE

Bus Duct

Diablo Canyon Bus Duct (OpE)
2000

Bus Duct Testing
2016

Columbia Bus Duct (OpE)
2009

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Conceptual Modeling Approaches

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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

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

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

Bounding ZOI (Current Model)

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- 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

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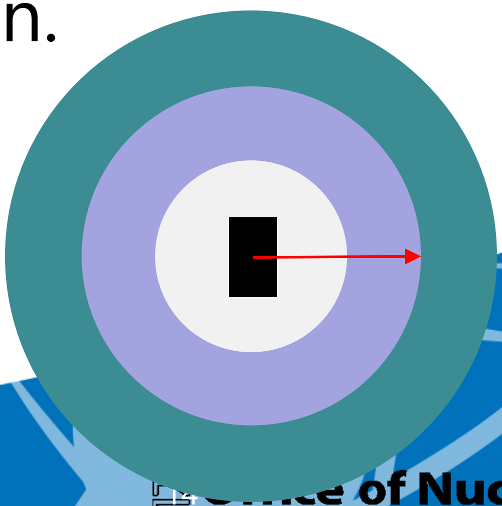
- Requires detailed information on power system
- Correlation from experiments and theory to model source term and incident flux as a function of distance
- Requires knowledge of fire PRA target fragility to high heat flux short duration.
- Potential to provide most realistic results
- Complex
- Most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



Modeling Approach

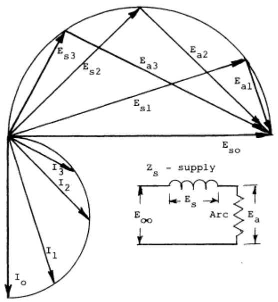
Status

- 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 appraoch
- NRC/EPRI working group advancing "PRA modeling" methodology

Overview of Existing Models

Theoretical

Lee Model



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- 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 > 15kV applications

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

Theoretical

Lee's Method

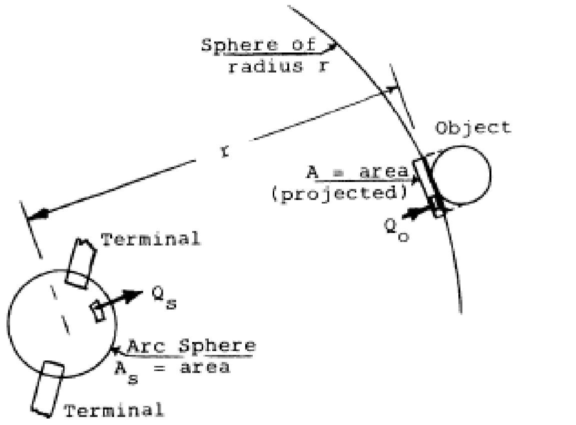

Fig. 1. Illustration of arc source and heat-receiving object.

- Output
  - IE, incident energy (J/cm^2) ← ASTM slug, T-cap. slug
- Inputs
  - V, system voltage (kV) ← KEMA Daq
  - t, arcing time (seconds) ← KEMA Daq
  - I_{bf}, 3 phase bolted fault current ← KEMA Daq
  - D, distance from arc point ← Physical Measurement

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

Semi-Empirical
Wilkins-Allison-Lang Method

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- Output
  - IE, incident energy
- 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
  - Ve, electrode voltage

ASTM slug

T-cap. slug

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
- Input
  - MVAsc, 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)

ASTM slug

T-cap. slug

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

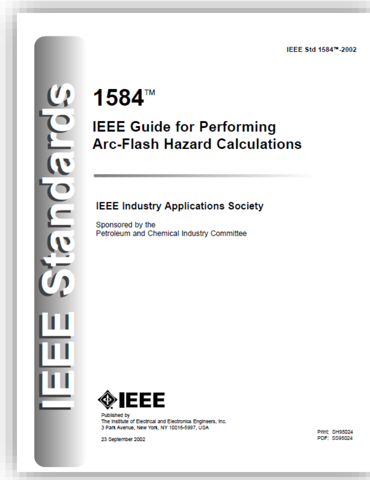
- Output
  - E_{MA},E_{MB}, Max. Incident Energy ← ASTM slug; T-cap. slug
- Input
  - F, 3-phase short-circuit current ← KEMA Daq
  - t_A, t_B, arc duration ← KEMA Daq
  - D_A,D_B, distance ← Physical Measurement

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

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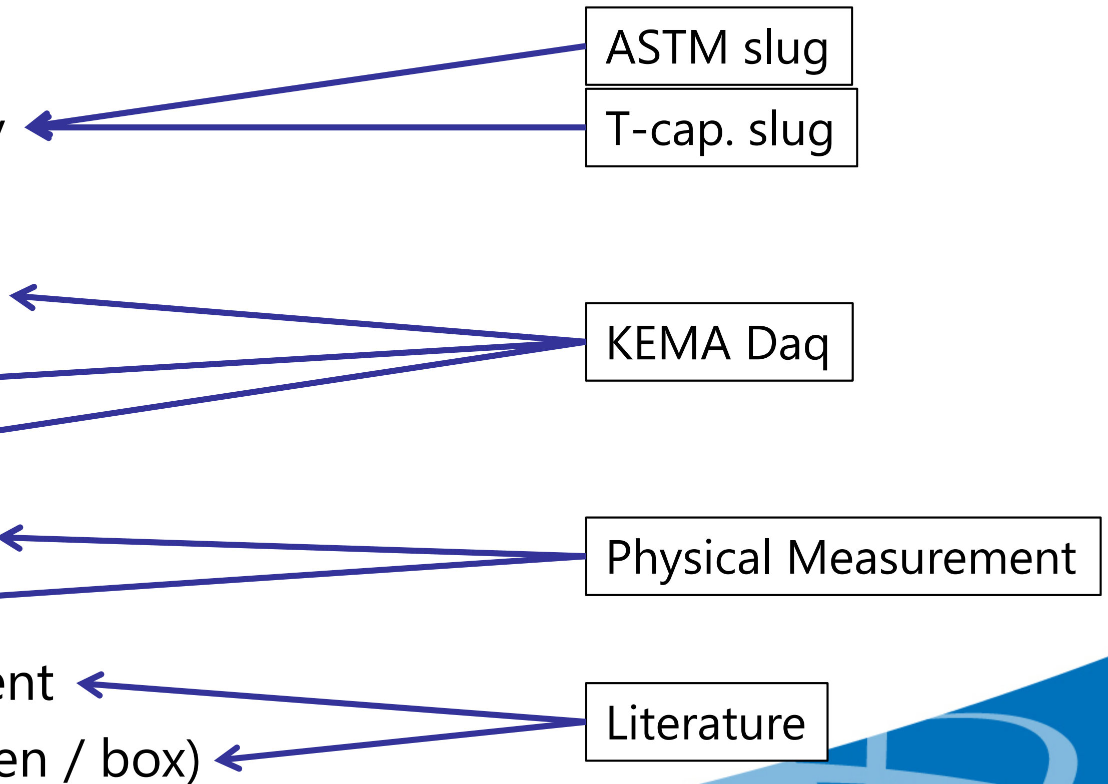
- Output
  - IE, Incident Energy
- Input
  - V, system voltage
  - I_a, arc current
  - t, arc duration
  - G, conductor gap
  - D, distance
  - x, distance exponent
  - Configuration (open / box)

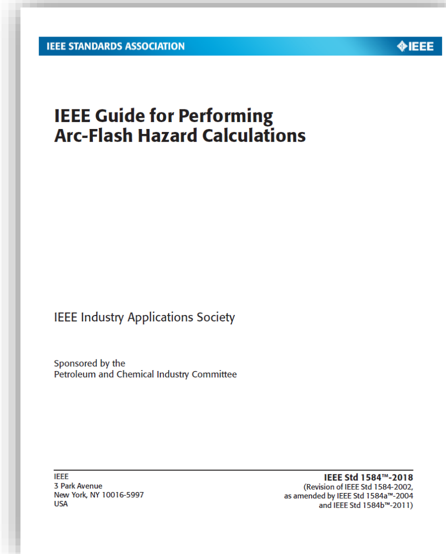


IEEE 1584-2002, *Guide for Performing Arc-Flash Hazard Calculation*, 2002

Empirical - Statistical

IEEE 1584 - 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 STANDARDS ASSOCIATION

IEEE Guide for Performing
Arc-Flash Hazard Calculations

IEEE Industry Applications Society

Sponsored by the
Petroleum and Chemical Industry Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 1584™-2018
(Revision of IEEE Std 1584-2002,
as amended by IEEE Std 1584a™-2004
and IEEE Std 1584b™-2011)

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

IEEE 1584 - 2018

Range of model

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- 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

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Empirical – Statistical

IEEE 1584-2018

- Output
  - IE, Incident Energy
- Input
  - I_{bf}, Bolted fault current
  - V_{oc}, System voltage
  - T, Duration
  - D, Distance
  - G, Conductor gap
  - Enclosure Dimensions
  - Equip Configuration

ASTM slug

T-cap. slug

KEMA Daq

Physical Measurement

Literature

Model Comparison

IEEE 1584 – 2018 vs MV Alum

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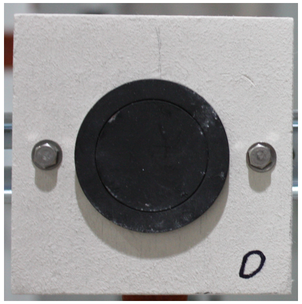
- ASTM slug calorimeter (copper)
  - Model overpredict max measured incident energy
    - Maximum overprediction : ~11x
      - 550 kJ/m^2 measured vs. 6,100 kJ/m^2 calculated
    - Minimum overprediction : ~2x
      - 3.4MJ/m^2 measured vs. 6.3MJ/m^2
      - Note: 2 instruments damaged due to HEAF damage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



Model Comparison

LEE vs MV Alum

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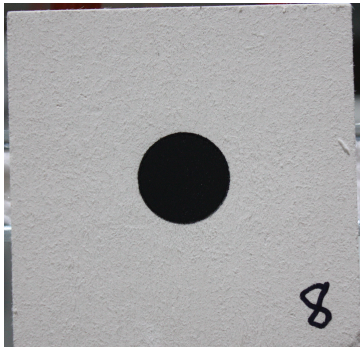
- ASTM slug calorimeter (copper)
  - Model overpredict max measured incident energy
    - Maximum overprediction : ~17x
      - 550 kJ/m^2 measured vs. 9,100 kJ/m^2 calculated
    - Minimum overprediction : ~3x
      - 3.4MJ/m^2 measured vs. 9.4MJ/m^2 calculated
      - Note: 2 instruments damaged due 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/m^2 measured vs. 6,100 kJ/m^2 calculated
    - Minimum overprediction : agreement
      - 6.0MJ/m^2 measured vs. 6.3MJ/m^2



Model Comparison

LEE vs MV Alum

- T-cap slug calorimeter (tungsten)
  - Model overpredict max measured incident energy
    - Maximum overprediction : ~39x
      - 236 kJ/m^2 measured vs. 9,100 kJ/m^2 calculated
    - Minimum overprediction : ~1.6x
      - 6.0MJ/m^2 measured vs. 9.4MJ/m^2

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.