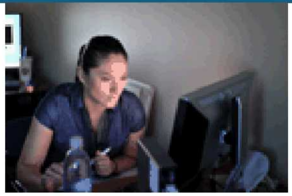
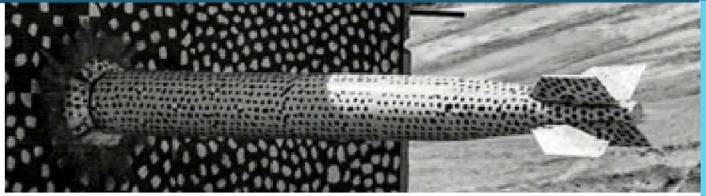
SAND2019-6934PE

Sandia Fire Research Program

Using analysis, modeling, and experimental validation of fire behavior to improve risk assessments for nuclear energy





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SAND2019-XXXX

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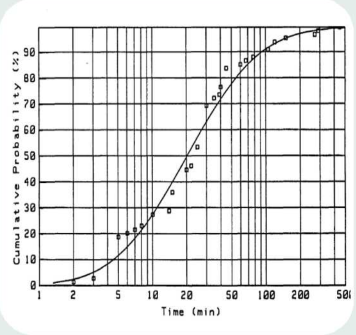
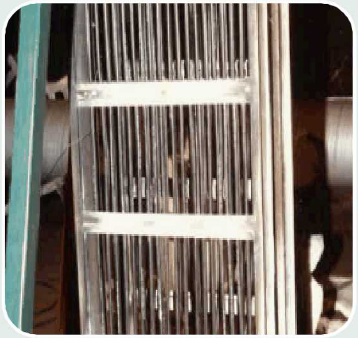
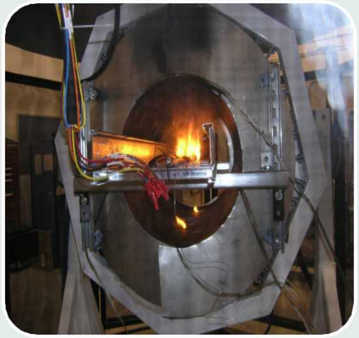
History of Sandia's Fire Research Program

Supporting nuclear fire science research for 40+ years







1970s

- SNL publishes first NUREG/CR on fire protection systems
- Cable tray fire tests

1980s

- Smoke/fire barrier tests
- Development of fire events database (start of fire risk)
- Suppression and detection effectiveness

1990s

- Cable aging tests
- Tests on the effects of smoke on digital equipment
- Reviewing fire risk/hazard analysis

2000s

- AC and DC cable performance testing
- Cable coating testing
- NUREG 6850 published on Fire PRA

2010s

- Arc fault testing
- Instrumentation cable performance testing
- NUREG 6850 improvements

Current HEAF Work

To develop the ability to quantify the damage that might result from a high energy arc fault event (HEAF event) in a nuclear power plant, and ultimately to prevent HEAF events from occurring

Developing model and resulting look-up table for:

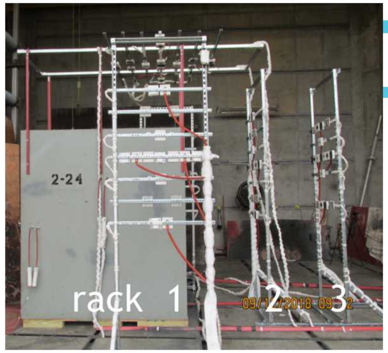
- Arc plasma emission as a function of current and gap
- Incident energy as a function of current, breach geometry, and electrode material
- Different components/equipment, such as switchgear, bus-duct, etc., based on OpEx
- Full-scale test data will be used to validate model predictions
- Determining ZOI based on fragility Flux/Temp and incident energy for varying electrode materials and geometries

Small Scale HEAF Testing

Experimental test bed for small scale (200A-1kA) HEAFs

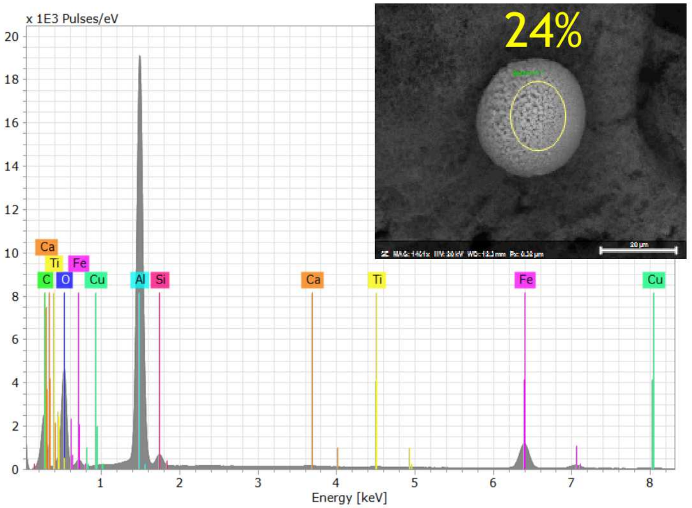
- Enables model validation
- Modifications to address NRC current and voltage targets

Large Scale HEAF Testing

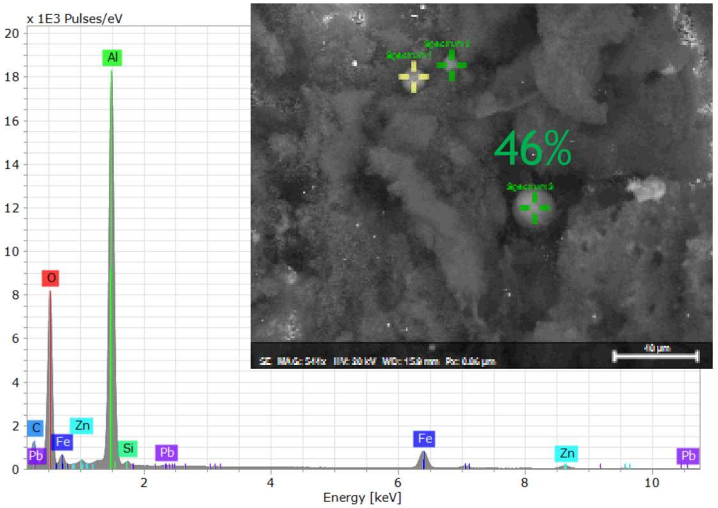


Particle collection: To quantify aluminum particle size and degree of aluminum oxidation and to correlate aluminum particle oxidation with distance from switchgear

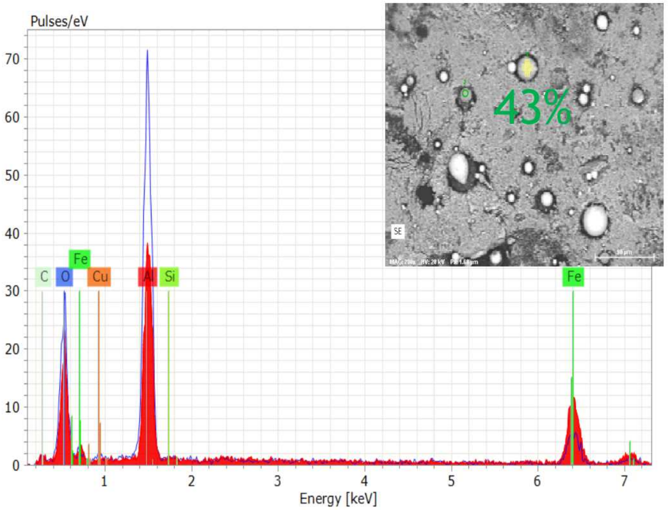
rack 1: right side, 44”



rack 3: front side, 88”



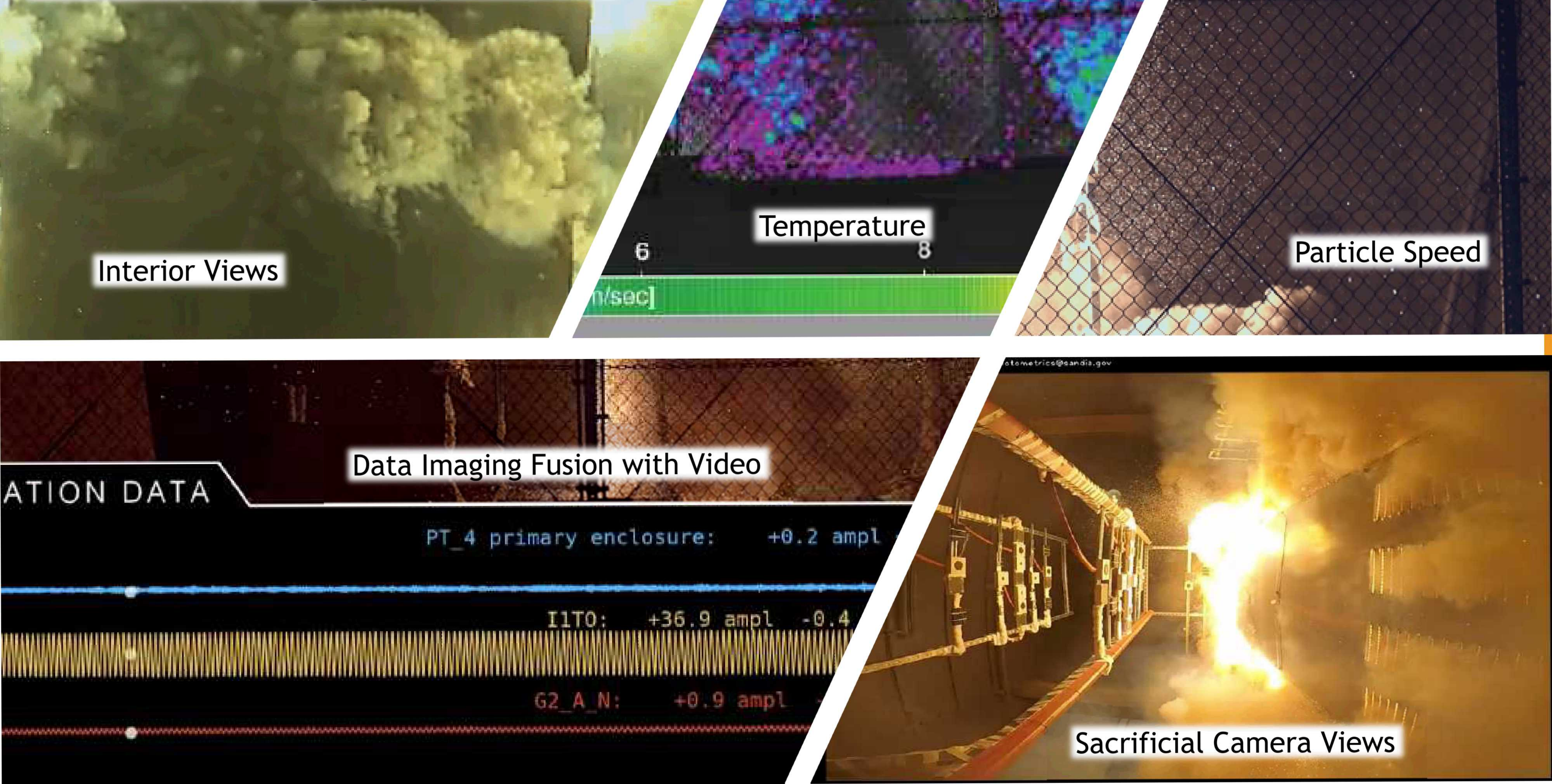
Tape from back wall plastic, 198”



Initial particle analysis:

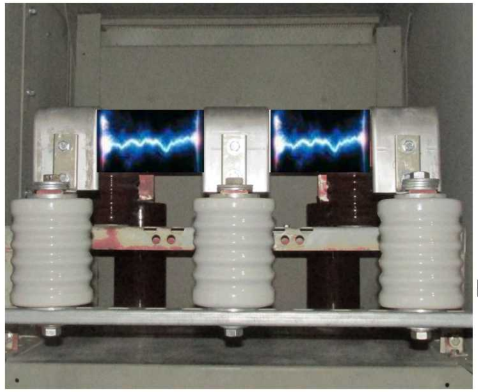
1) micron sized Al particles display 24-70% oxidation (melted in arc + solification/surface oxidation)
2) Al nanoparticles appear 70-100% oxidized (vaporized + oxidation)

Sandia Data Imaging Capabilities



HEAF Modeling Overview

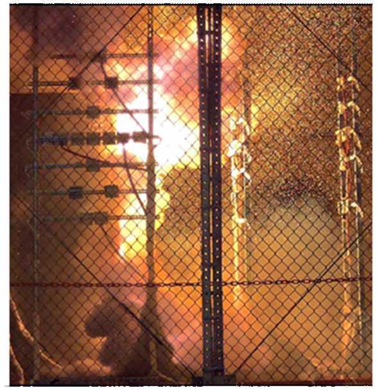
Best estimate of credible energy release scenarios and respective zones of influence for range of appropriate equipment at NPP. Easy to follow methodology and guidance on how and when to apply the ZOI within the FPRA



current, gap

Aria

plasma temperature,
thermal field,
radiative transfer,
convective transfer



sooty flame,
cabinet geometry,
gas expansion

Fuego

blackbody radiation,
thermal fields,
incident energy,
zone of influence

<u>Aria (arc-fault model) :</u>

Inputs: arc current, gap distance

Outputs: - plasma temperature (~10000K)

- radiative & convective heat transfer

<u>Small scale experiments:</u>

Confirm plasma temperature

Confirm blackbody spectrum

Measure radiative energy transfer

Black plate calorimeters

Measure thermal field

Schlieren imaging of air temp

<u>Fuego (sooty flame model):</u>

Absorption and blackbody emission (≤3000K)

Fuego outputs: - flame temperature

- gas expansion of flame
- radiative heat transfer
- convective heat transfer
- thermal fields

<u>KEMA experiments:</u>

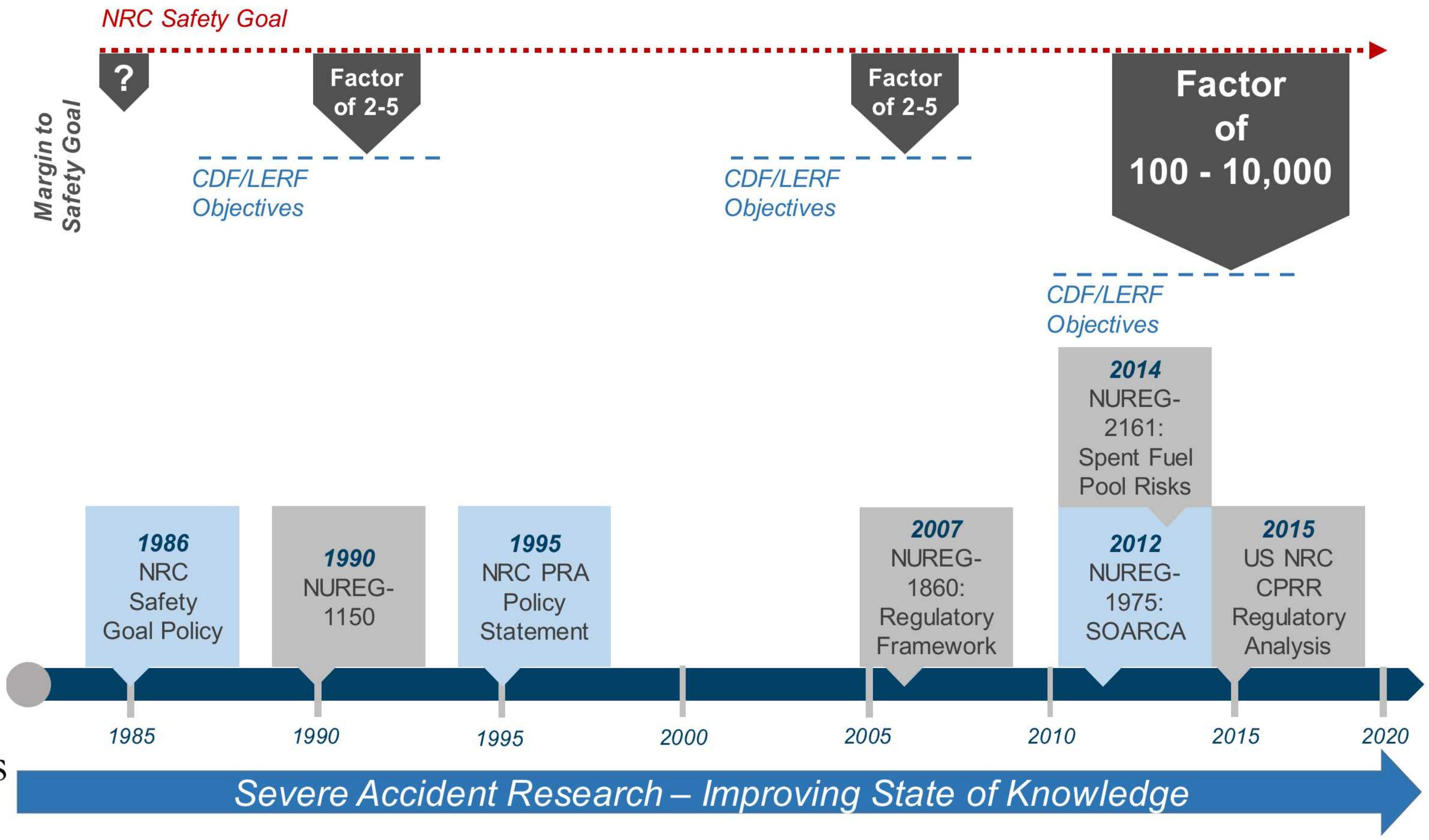
Measure "sooty flame" temperature

Confirm blackbody spectrum

Measure convective flow, incident energy

Evolution of Severe Accident State of Knowledge

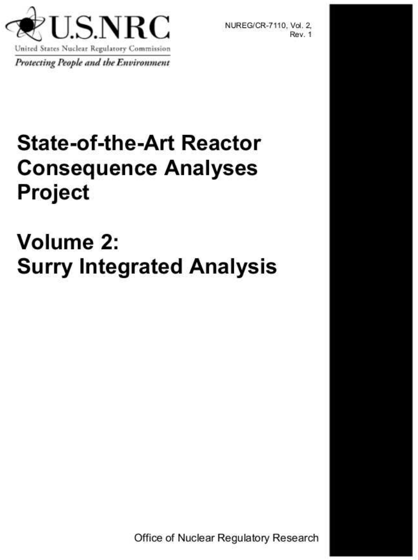
- Significant investment over 30 years
  - Understanding of severe accident phenomena
  - Development of computer codes to represent severe accident progression
  - Studies of best estimate severe accident progression
  - Development of severe accident uncertainty analysis technology
- Expansion of risk-informed decision-making
- Occurrence of Fukushima Daiichi
  - New perspectives on reactor scale severe accident progression
- How are legacy assumptions in PRAs affected?



Implications from Evolution of Severe Accident State of Knowledge
RCS Depressurization after Core Damage

In early PRAs, implications of high pressure RPV/RCS failure more significant

- Potential for thermally-induced SGTR (TI-SGTR) following onset of core damage less well understood
- RPV lower head breach with vessel at high pressure assumed more likely
  - Led to significant past effort studying high-pressure melt ejection (HPME) and Direct Containment Heating (DCH) consequences
- Surry SOARCA spent significant effort to refine understanding of potential for hot leg creep rupture (HLCR) relative to TI-SGTR
  - Hot leg creep rupture dominates realizations
  - Approximately 10% of cases realized TI-SGTR instead of HLCR
  - No scenarios with high pressure RPV lower head breach

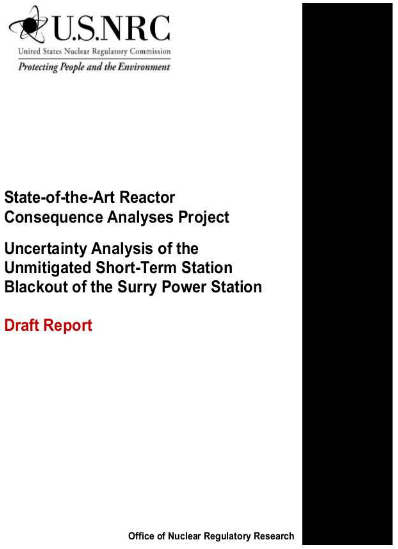

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-7110, Vol. 2, Rev. 1

State-of-the-Art Reactor Consequence Analyses Project

Volume 2: Surry Integrated Analysis

Office of Nuclear Regulatory Research


U.S.NRC
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Protecting People and the Environment

State-of-the-Art Reactor Consequence Analyses Project

Uncertainty Analysis of the Unmitigated Short-Term Station Blackout of the Surry Power Station

Draft Report

Office of Nuclear Regulatory Research

Severe Accident Pressure Fuse

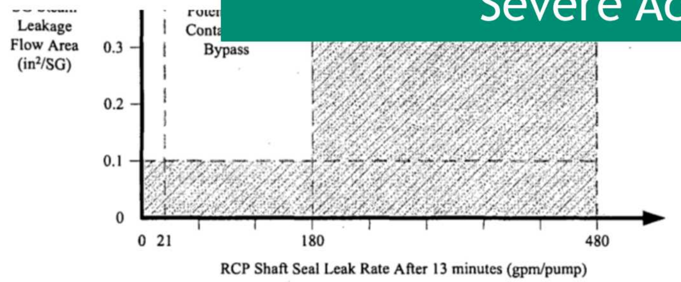
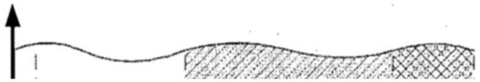
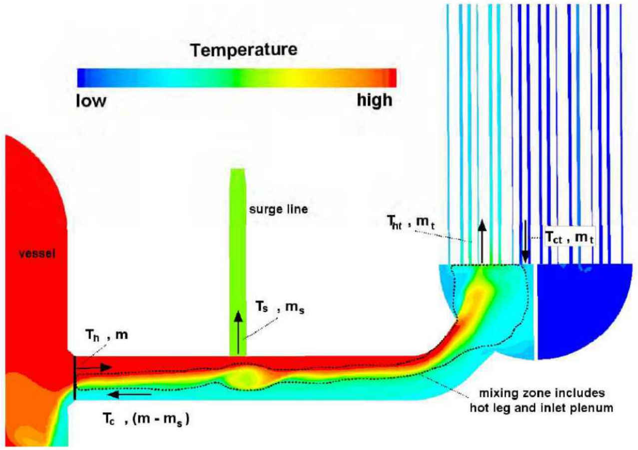
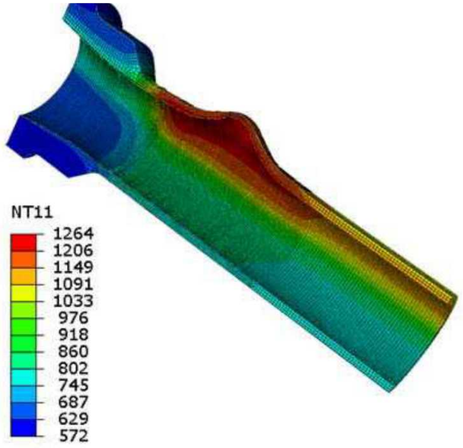


Figure 6.1 Map of Containment Bypass Outcome for No Operator Intervention and Variations in SG Steam Leakage and RCP Shaft Seal Leakage Which Increases at 13 Minutes



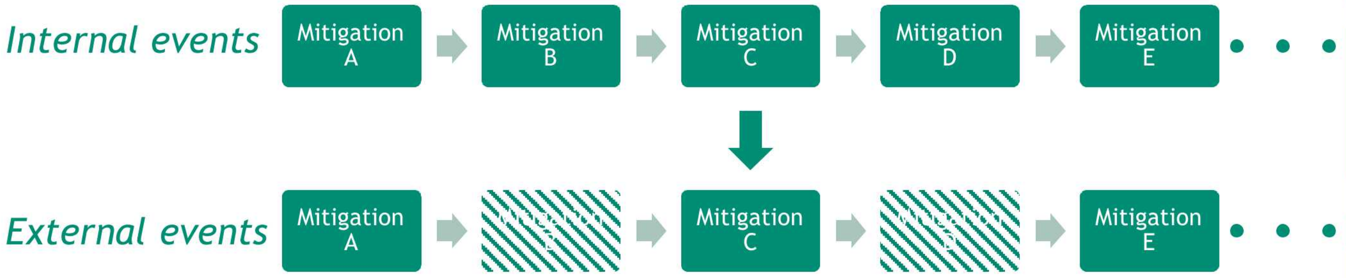


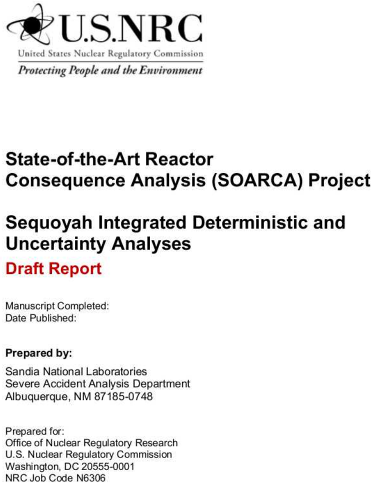


Implications from Evolution of Severe Accident State of Knowledge
State-of-the-Art Reactor Consequence Analyses (SOARCA)

Many legacy Level 2 assumptions in PRAs have evolved from internal events PRAs
- These assumptions have typically not driven internal event PRA results (e.g., LERF)
- Often made for expediency or to bound prevailing knowledge gaps in past

Consider Ice Condenser plant
- Conditional containment failure probability aided by availability of hydrogen igniters
  - Core damage does not imply containment failure (large early release)
- DC power is typically available across many dominant cutsets in internal events PRA
  - Hydrogen igniters are available
- For DC power loss cutsets, expedient to assume containment failure due to hydrogen combustion
  - Generally not dominant in internal event PRAs
- A range of external events could consequentially fail DC power
  - Hydrogen igniters unavailable
  - LERF becomes similar to CDF without credit for DC power
- Severe accident uncertainty analyses developed for Sequoyah SOARCA
  - Much lower likelihood of containment failure due to hydrogen combustion

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State-of-the-Art Reactor Consequence Analysis (SOARCA) Project

Sequoyah Integrated Deterministic and Uncertainty Analyses

Draft Report

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Washington, DC 20555-0001
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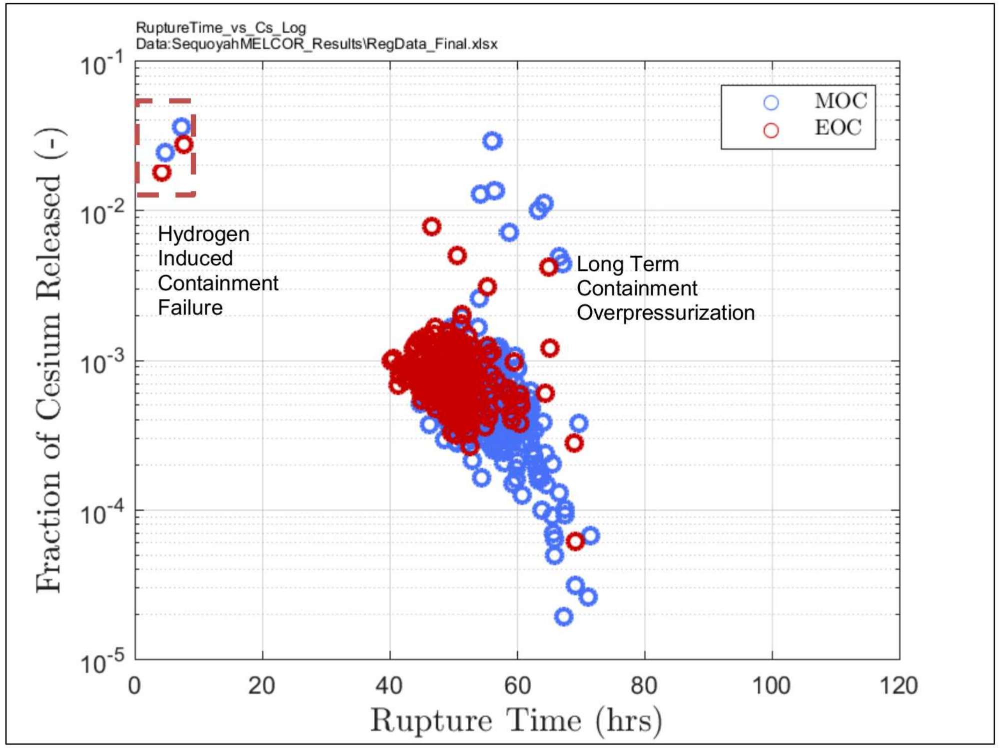
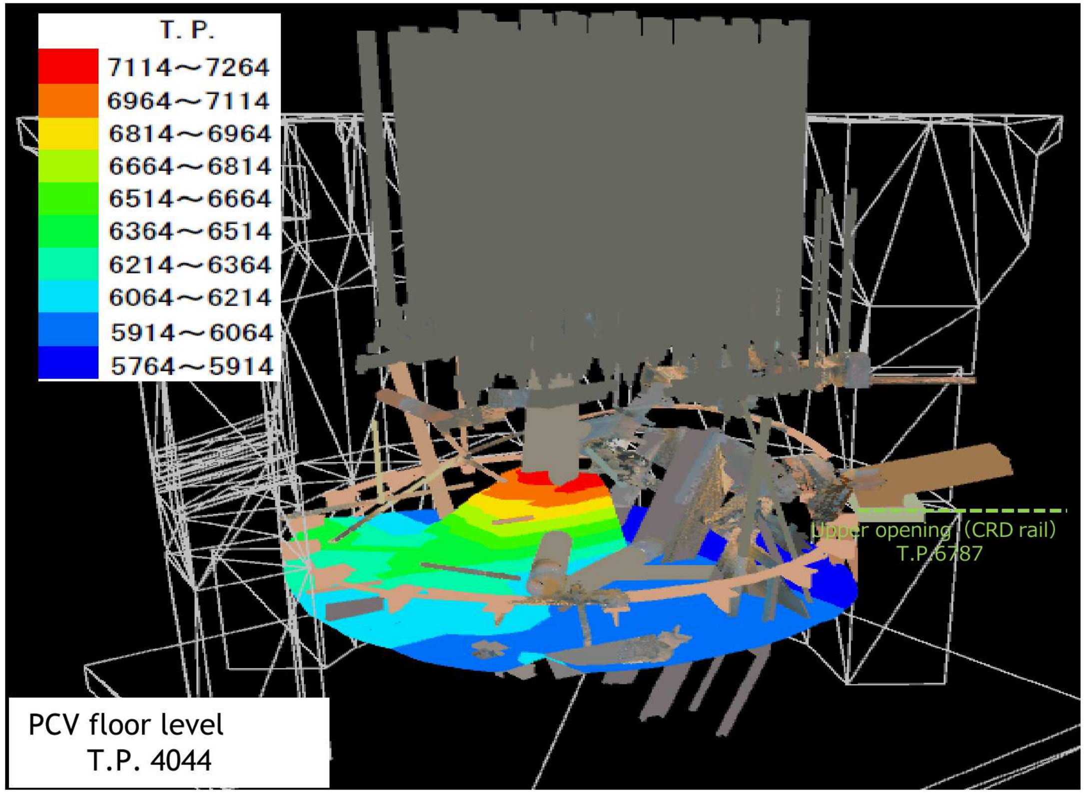


Evolving Severe Accident State of Knowledge
Fukushima Daiichi

Fukushima Daiichi Units 1, 2 and 3 progressed to ex-vessel core damage
- Three fundamentally different accidents
  - Unit 1 unmitigated
  - Units 2 and 3 partially mitigated
- Three different damage end states

Ex-vessel core damage conditions most important contribution to knowledge base
- Unit 1 has had late failure of containment floor despite no water injection for a few days
  - Debris has appeared to spread like viscous lava
- Unit 2 has peripheral lower head failure
  - ~80% of debris in lower plenum
  - Largely metallic debris on reactor pedestal floor
- Unit 3 has debris localized within reactor pedestal
  - Large solid debris mass under center of vessel



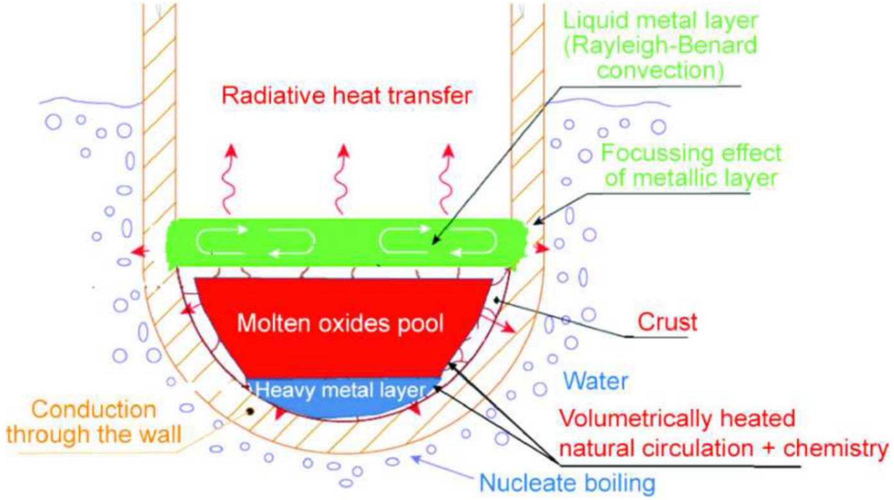
Implications from Evolving Severe Accident State of Knowledge
RPV Lower Head Breach

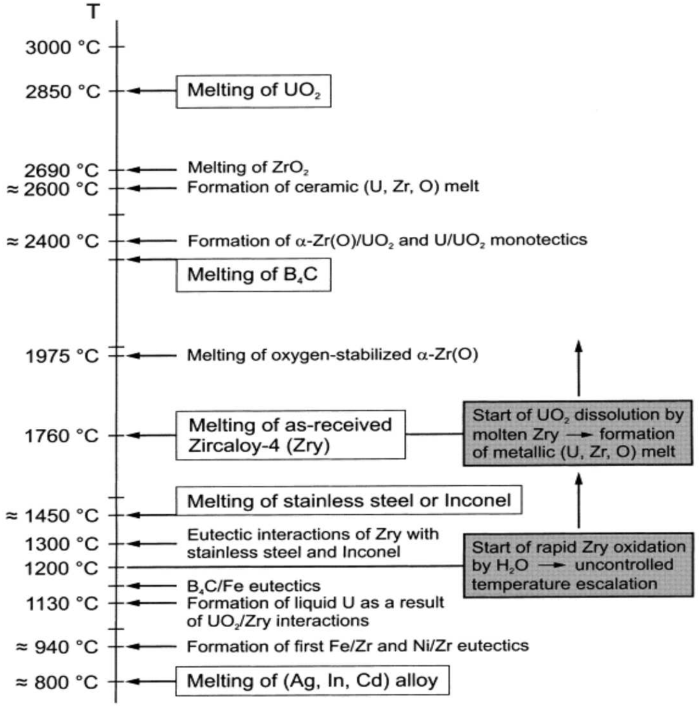
Fukushima Daiichi indicating earlier vessel breach than models currently estimate
- Lower head failure prior to build-up of large molten debris pools in lower plenum

Past models based on non-prototypic conditions
- Focus on ability of lower head to resist heat loads from molten debris beds
- No consideration of complex material interactions of debris with lower head steel wall
  - Low temperature dissolution uncooled lower head wall
  - Low temperature Fe eutectic interactions with material in debris

Large mass of oxidic debris remains largely solid at time of vessel breach
- Relocation of material occurs as debris melts and moves out of pre-existing failure

Severe Accident Thermal Fuse





Implications from Evolving Severe Accident State of Knowledge

Ex-Vessel Damage

Largely solid debris upon lower head breach presents different ex-vessel damage perspective

- Debris relocates as it melts
- Highly viscous slurry relocating into containment
- Enhanced freezing on any below-vessel structures

Rate of debris relocation governed by rate at which debris melts

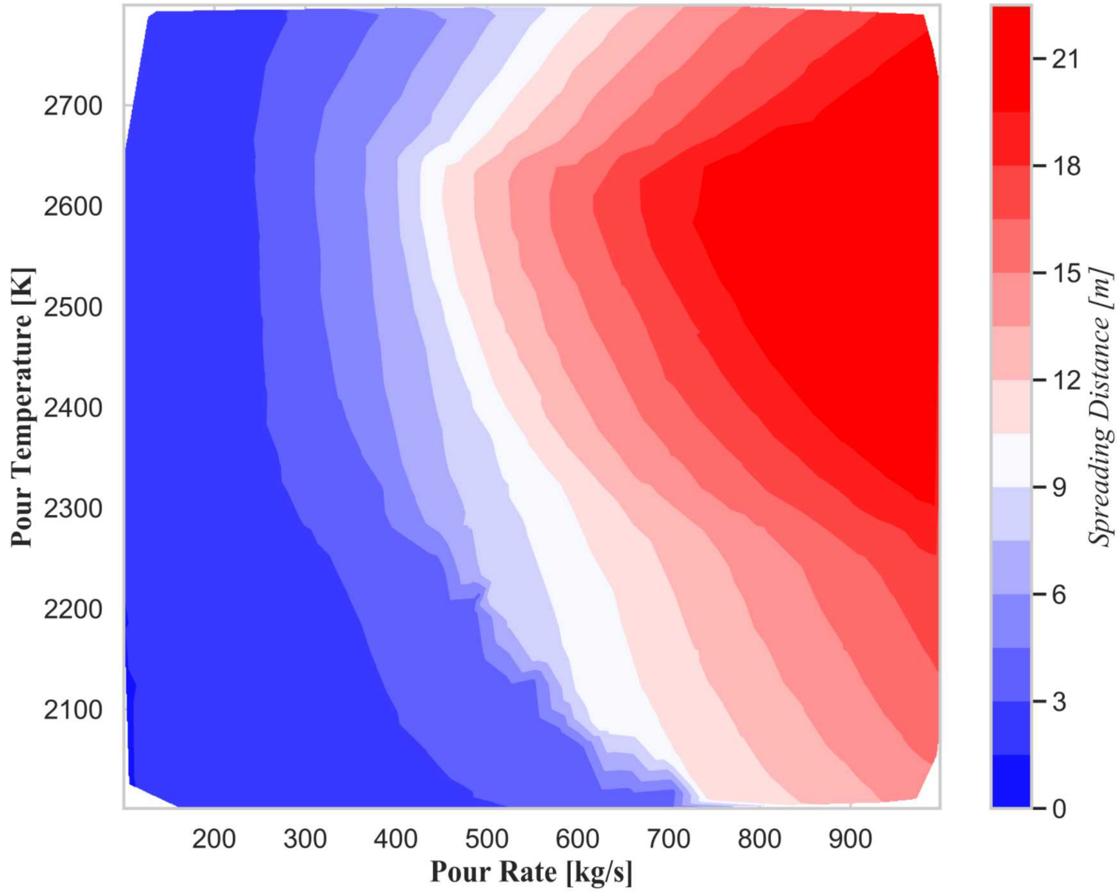
- May have very brief bursts of material relocation due to peripheral debris slumping from reactor core
- From EPRI SAMG TBR: debris melting rate ~350kg/s

Ex-vessel damage conditions in containment influenced by

- Rate of debris relocation
- Temperature of relocating debris
- Duration of debris pour

State-of-the-art modeling with MELTSPREAD indicates limited debris spreading

Highly particulate, "chunky" debris more readily cooled when water introduced into containment



Implications from Evolving Severe Accident State of Knowledge
In-Vessel Retention and Fukushima Daiichi Unit 2

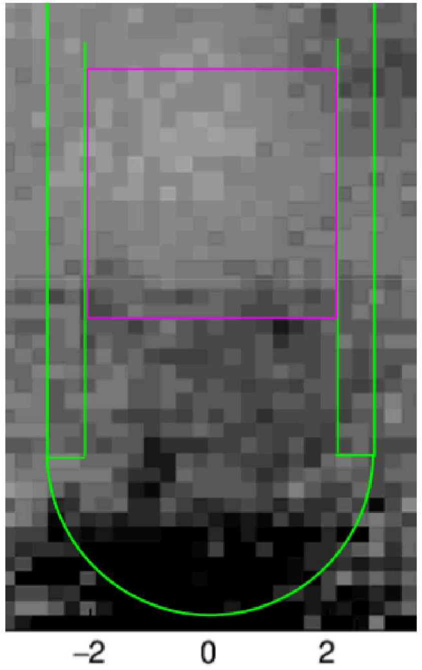
In-vessel retention strategies provide external and potentially internal cooling

- Fukushima Daiichi Unit 2 highlights important role of water injection in maintaining large fraction of debris inside vessel

Water injection provides an effective means to prevent thermal excursions in lower head wall

- Preventing lower head wall temperature thermal excursion eliminates activation of lower head "thermal fuse"

Unit 2 Muon Tomography



Unit 2 CRD Forest

Further Evolution of Severe Accident Progression Realism

Advances in severe accident knowledge base

- Have shown a more gradual evolution of accident progression

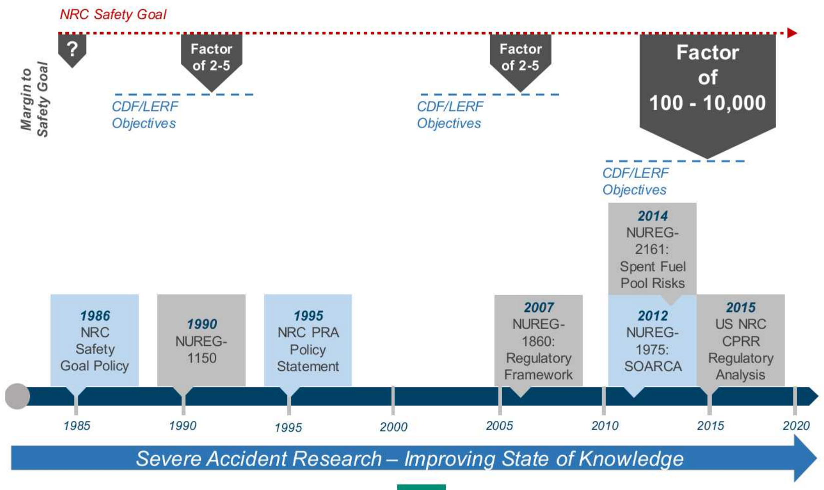
Events that lead to large energy release into containment less likely to occur or cause failure of containment boundary

Occurrence of challenge to containment structural integrity more slowly evolving

- Decay heat rejection leads to
  - Slow build-up of containment pressure and temperature
  - Mechanical challenge to structural boundary
  - Thermal-mechanical challenge to containment polymeric seals

Pressure/Thermal Fuses exist that tend to fail before significant mechanical or thermal "charge" builds up in the system

- Hot leg creep rupture
- Early RPV lower head breach



Severe Accident Pressure Fuse

+

Severe Accident Thermal Fuse

Thank you

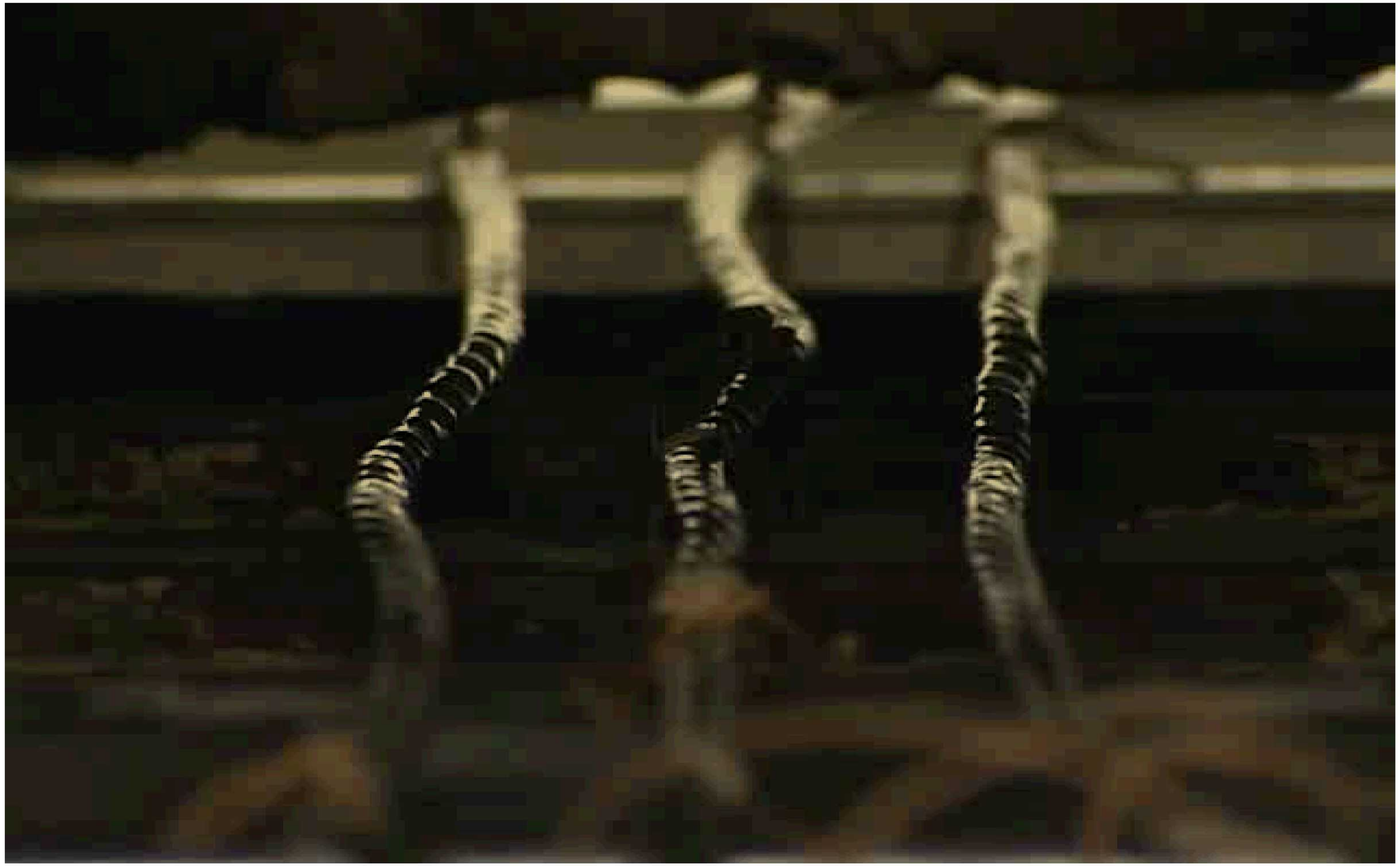
Backup Slides

Key Experimental Programs

Characterizing fire behavior in nuclear-specific applications

- Cable performance when exposed to thermal environment
- Circuit reliability
- Validating complex models
- Using state-of-the art instrumentation to study high energy arc faults (HEAFs)

Supporting NRC in Fire PRA development



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