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Approach to Address Core Coolability Issues with Failed Fuel

RIA Workshop on RIA

October 16, 2007

Robert Montgomery

Presentation Overview

- Introduction
  - Experimental Justification for Separate Failure Threshold and Core Coolability Limit
  - Requirements for Demonstrating Coolability from Interim RIA Acceptance Criteria

- Industry Approach to Demonstrate Coolability
  - Flow blockage from fuel dispersal and clad ballooning
  - Mechanical energy generation from fuel dispersal

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Justification for Maximum Enthalpy Limit Above Failure Threshold

- Experimental Observations
  - Majority of failures with peak fuel enthalpy above interim failure threshold maintained rod geometry
  - Consequences of fuel dispersal did not lead to damaging pressure pulses or loss of rod geometry

- Other Assessments Support Separate Criteria
  - Nuclear Safety Commission of Japan (NSCJ), Swedish Safety Authority (SKI), Switzerland (HSK), others
  - Technical evaluation included fuel dispersal

- Analytical Evaluations (RETRAN analysis, others)
  - Pressure pulse generation from dispersal of non-molten material will likely be within the reactor pressure vessel limits
  - Needs demonstration

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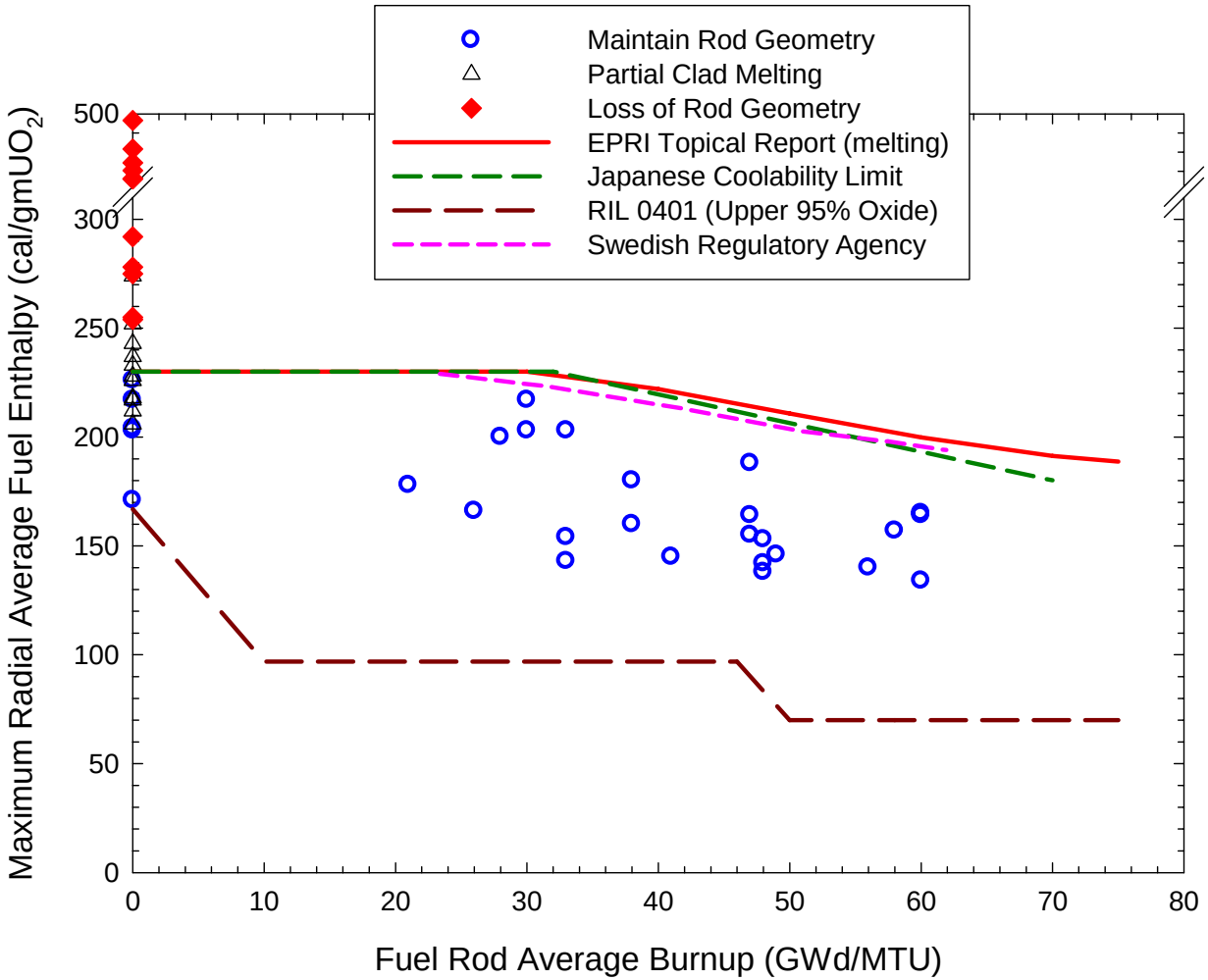
Experimental Results for High Burnup Failures



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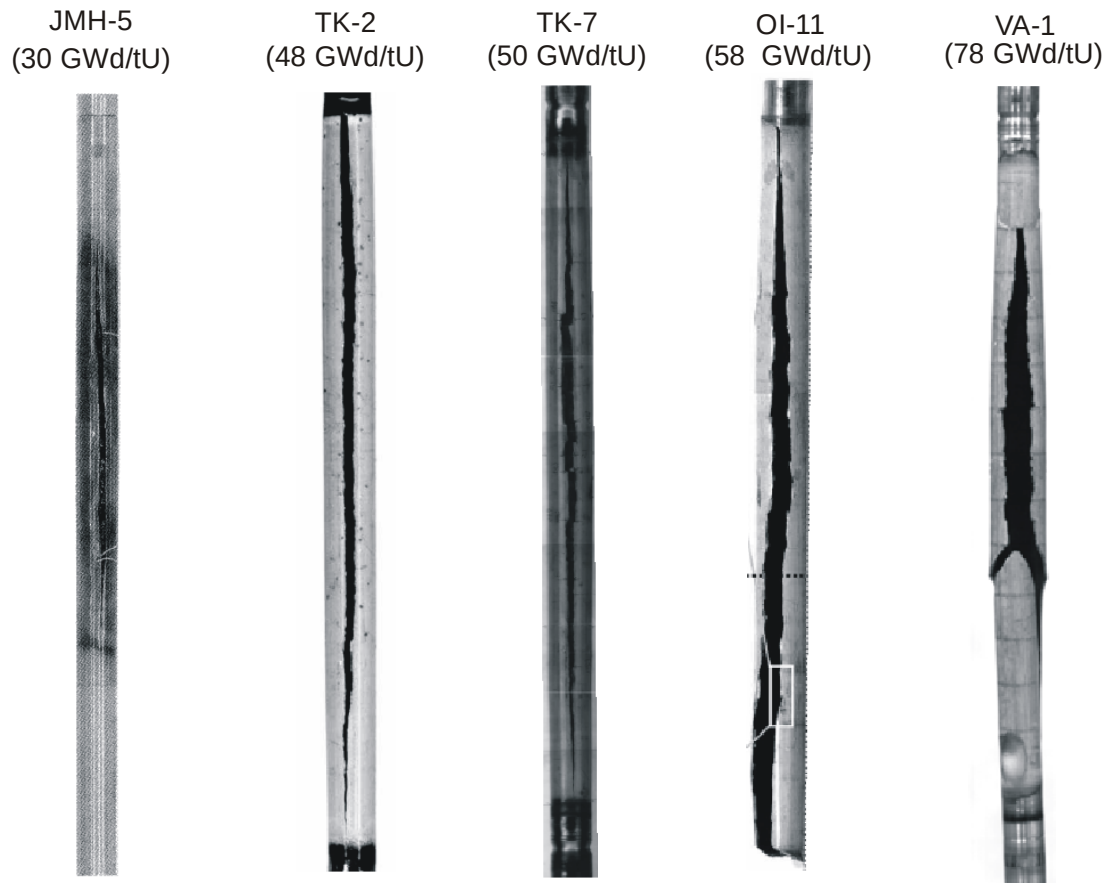
Visual Appearance After Fuel Dispersal (Intermediate and High Burnup Fuel)

NSRR Experiments

Pulse widths: ~4 ms

Rod Length: 5 to 6 in

Uniform Axial Power



220 cal/gm | 107 cal/gm | 95 cal/gm | 157 cal/gm | 127 cal/gm

Maximum Radial Average Peak Fuel Enthalpy

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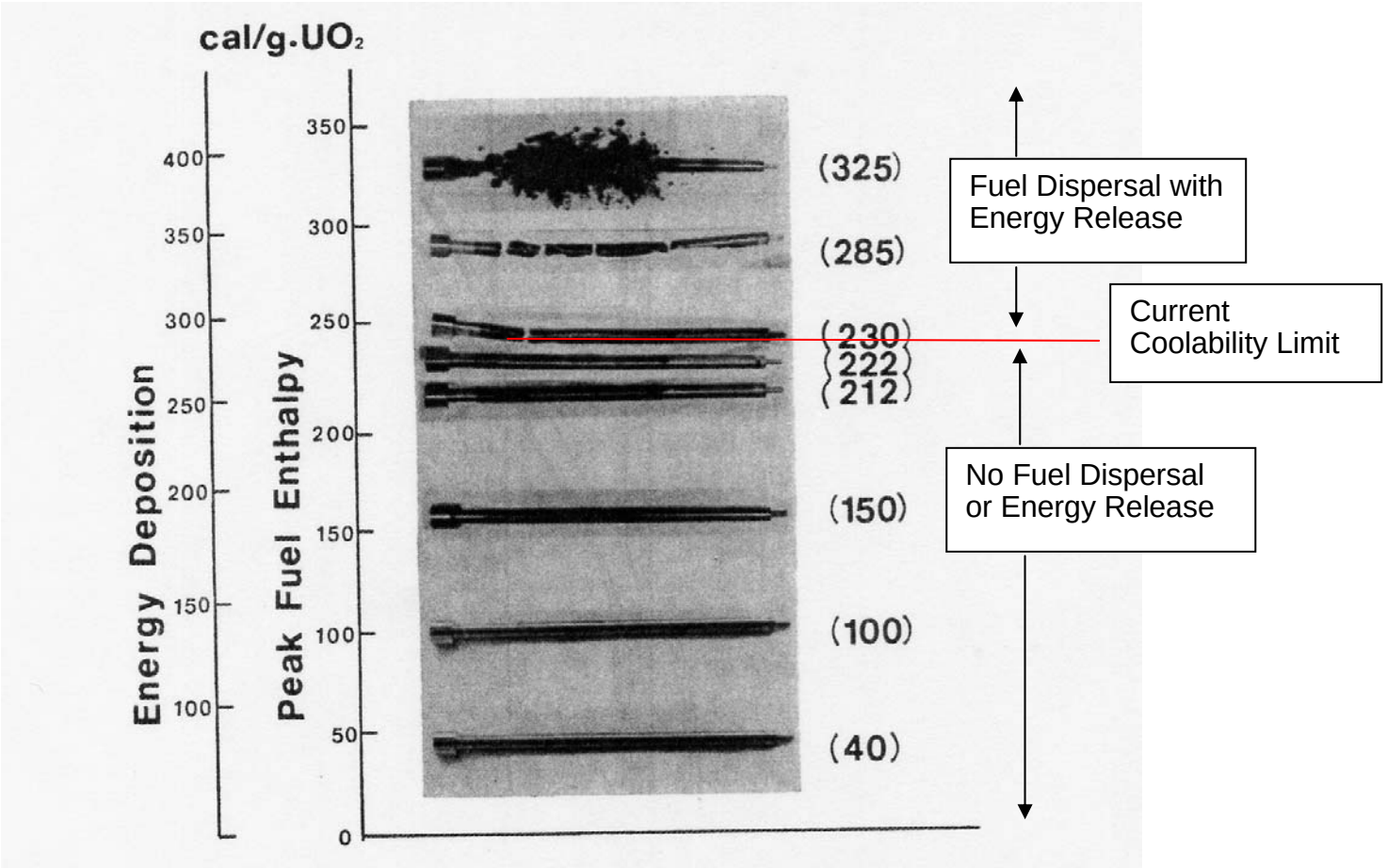
Appearance of Unirradiated Test Rods After RIA Experiments



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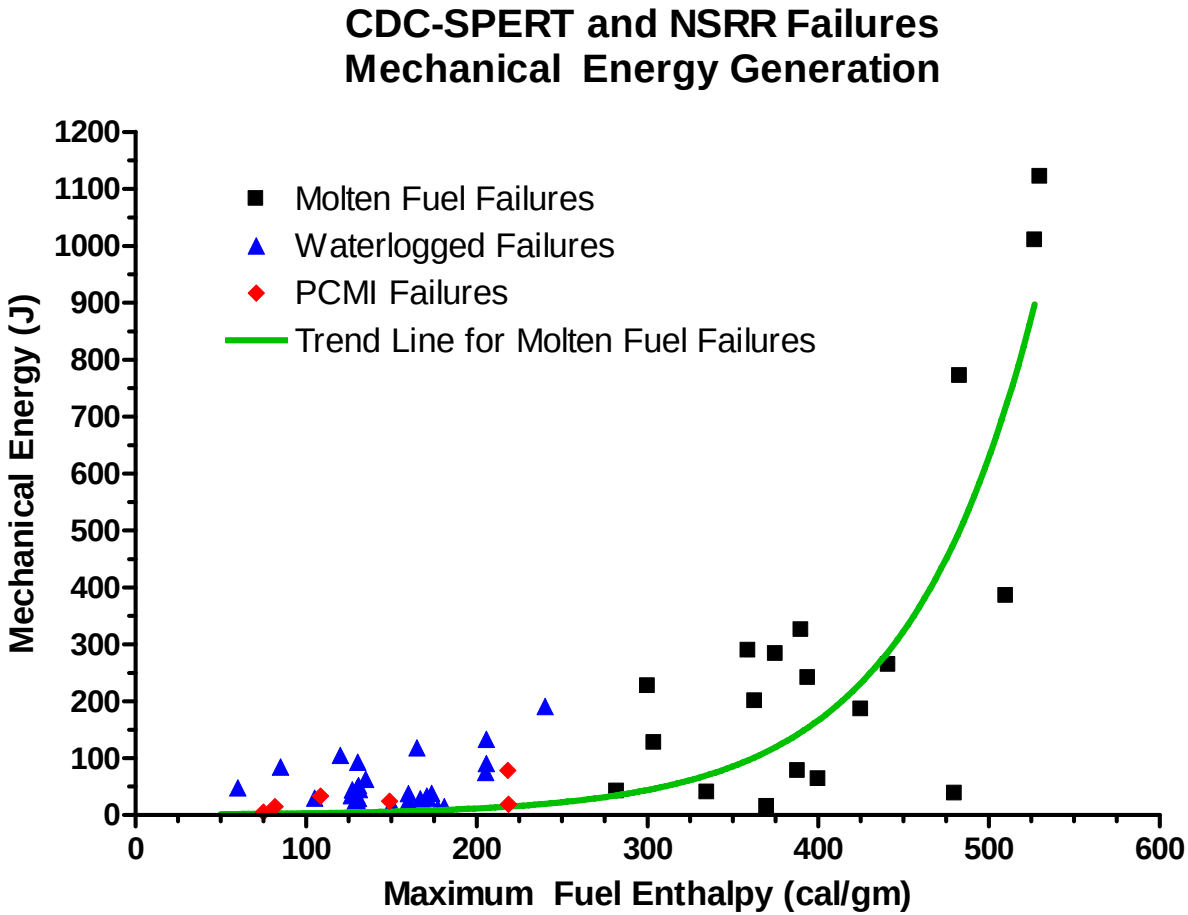
Mechanical Energy Generation after Cladding Failure – Experimental Results



Consequences of PCMI failure for irradiated fuel are much lower than for molten fuel failure

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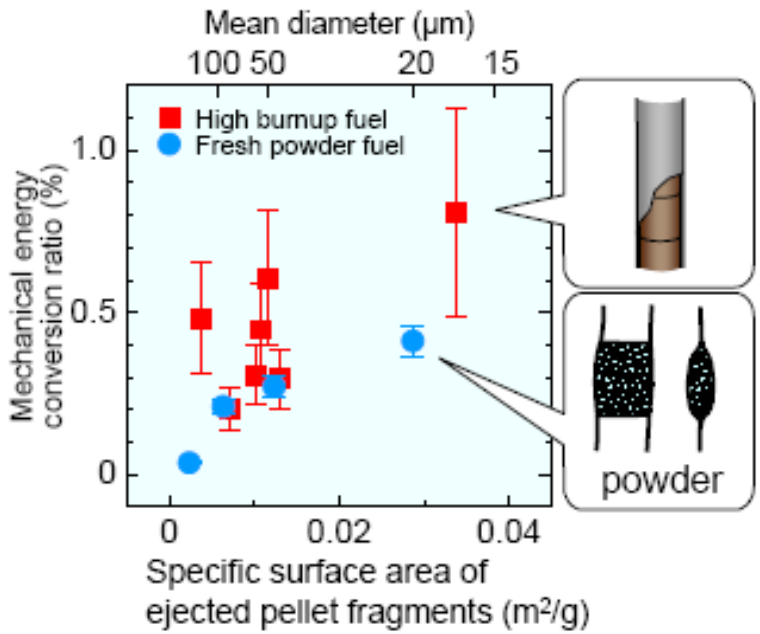
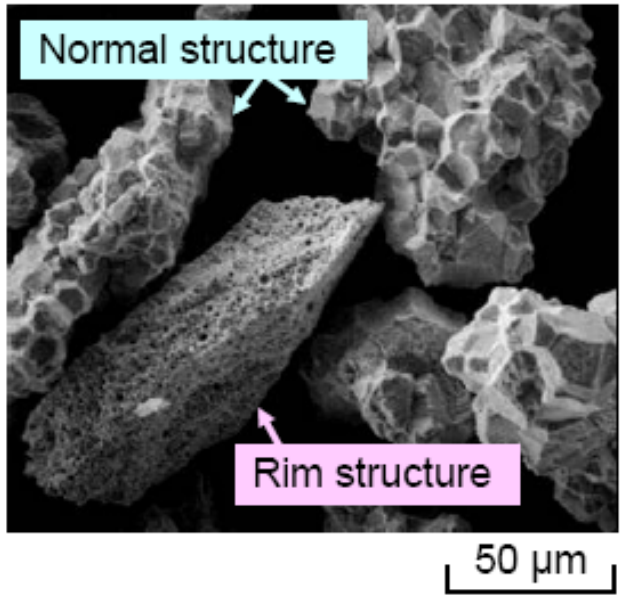
Particle Size in Dispersed Fuel

Sugiyama presentation, May 2007 FSRM - Tokia



Fragmented pellets (BWR fuel, 61 GWd/t)



<u>Mean Particle Size:</u>

- No endplug/cap failure – 15 – 20 microns
- With endplug failure - > 50 microns
- Small fraction of particles < 5 microns
- Particle size appears to be burnup independent

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Interim Criteria for Core Coolability

1. Peak radial average fuel enthalpy < 230 cal/gm
2. Peak fuel temperature below incipient melting conditions
3. Mechanical energy generation effects on reactor pressure boundary, reactor internals, and fuel assembly structure from;
   - Non-molten fuel-coolant interaction (FCI)
   - Fuel rod burst
4. No loss of coolable geometry due to;
   - Fuel pellet and cladding fragmentation and dispersal
   - Fuel rod ballooning

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Demonstrating Compliance to Core Coolability Criteria – Licensee Options

Option 1

- No cladding failures for all rods or beyond a burnup where high burnup rim structure formation occurs

Option 2

- No fuel dispersal upon failure based on power pulse characteristics and failure mode
  - May still need to address flow blockage by ballooning

Option 3

- Demonstrate consequences of fuel dispersal and ballooning have no impact on both short-term and long-term core coolability

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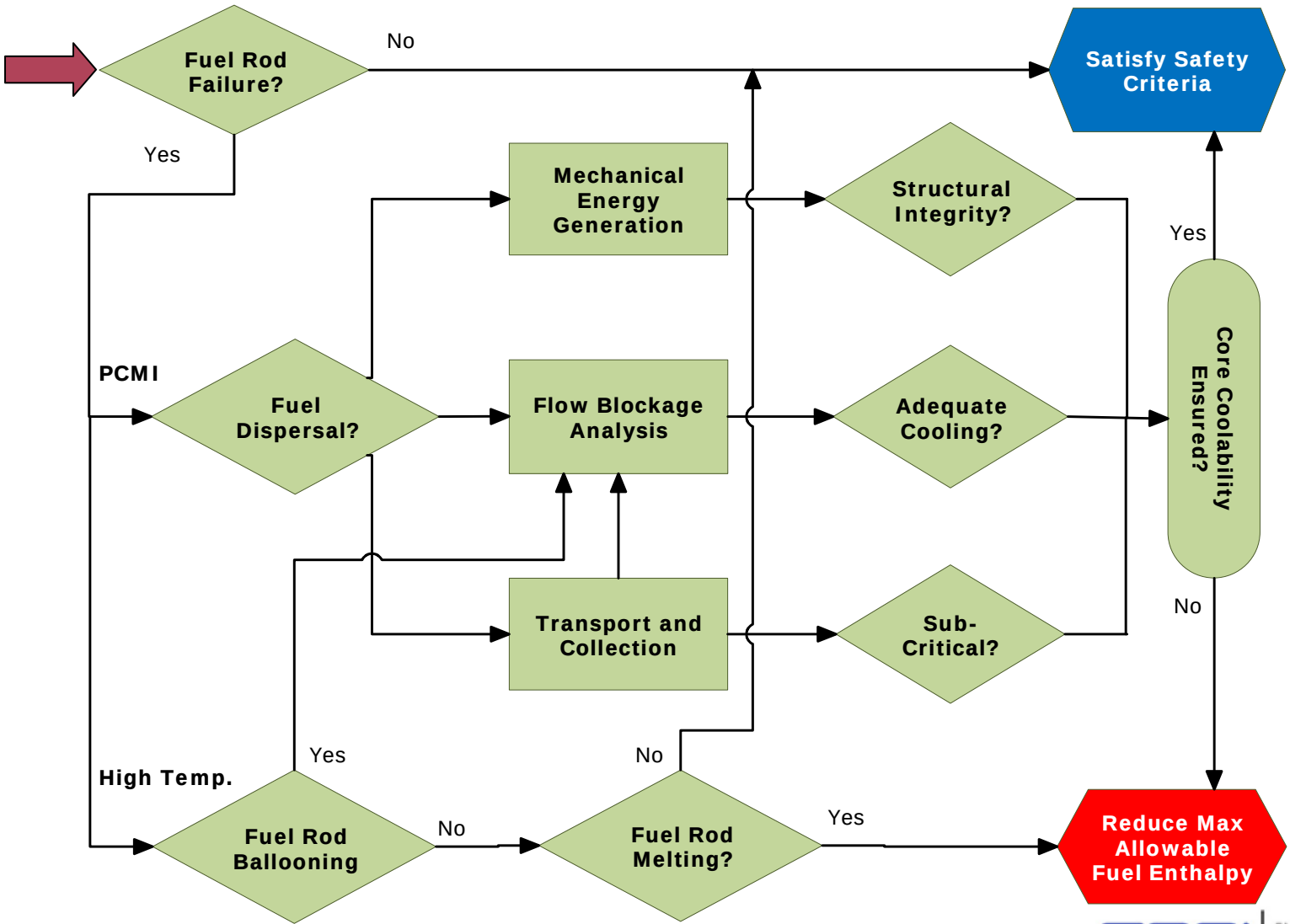
Demonstrating Compliance to Core Coolability Criteria – Flow Diagram



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Industry Approach: Separate Coolability Concerns into Two Parts

- Long-term coolability (t > 5 seconds)
  - Address effects of flow blockage due to fuel fragmentation and rod ballooning
  - Address effects of fuel particle transport in the primary coolant system
  - Bound these effects using another higher probability accident such as LOCA

- Short-term coolability (t < 5 seconds)
  - Address mechanical energy generation from non-molten Fuel-Coolant Interaction and release of rod pressure

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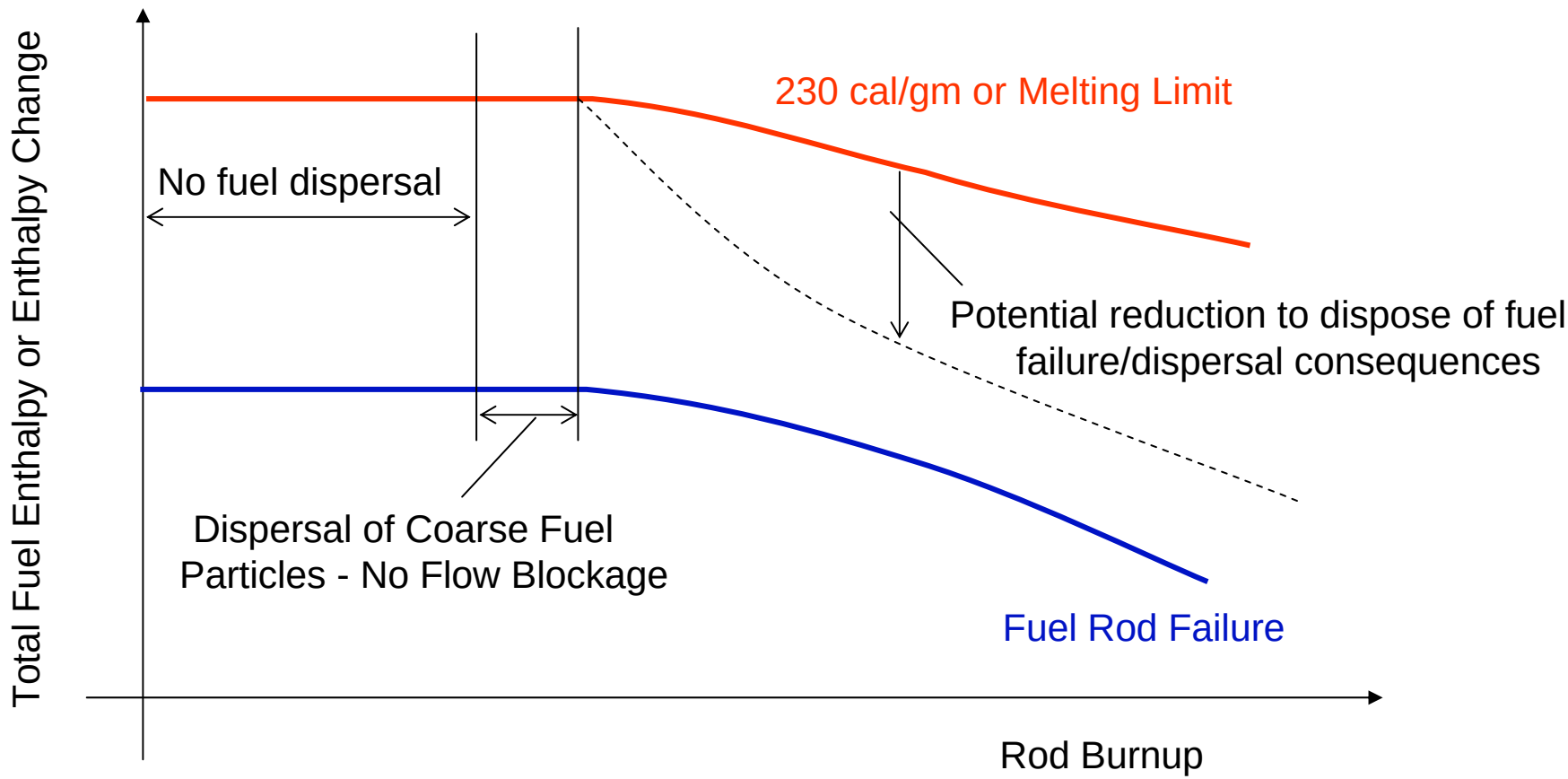
Schematic of RIA Acceptance Criteria



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Overall Approach to Define Coolability Limit

- Vendors/Licensees to provide fuel design/plant design specific assessments
  - Incipient fuel melting enthalpy limit (#2)
  - Long-term coolability issues (#4)
  - Fuel dispersal/burst, mechanical energy generation, and RCS integrity assessment (#3)

- EPRI FRP-WG2 to provide example/generic methodology to address short-term coolability issues (#3)
  - Mass and energy of dispersed fuel
  - Mechanical energy generation from dispersed fuel and pressure release after burst
  - RCS integrity assessment

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Industry Approach to Long-Term Coolability (PWR and BWR)

- Flow blockage from clad ballooning and fuel dispersal
  - Use LOCA to demonstrate flow blockage from clad ballooning and fuel dispersal will not lead to loss of coolable geometry

- Transport of fuel particles within the primary coolant system
  - Use LOCA to demonstrate that criticality and cooling of debris bed will not lead to loss of coolable geometry

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Does LOCA Bound Flow Blockage from Clad Ballooning in RIA?

- How big is the affected region of the core?
  - Smaller region of the core experiences clad ballooning in RIA event
- Are the cladding deformations the same?
  - Balloon size will be smaller in RIA
- How do the flow blockage conditions compare?
  - Smaller affected region, less channel reduction, and full flow conditions lead to lower potential for flow blockage

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Core Region with Clad Ballooning

- Calculations using NUREG-0630 criteria show 10 to 20% of the rods fail by clad ballooning in LBLOCA
  - Recent EU assessment

- Worst case estimates show <5% of fuel rods could experience clad ballooning in RIA event
  - Ballooning failure most likely in lower burnup fuel < 30 GWd/tU
  - DNB not likely in high burnup fuel (PCMI dominates)

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Clad Balloon Characteristics in RIA

- High temperature burst in $\alpha+\beta$ phase leads to low burst strains
  - Experience from NSRR and IGR/BIGR tests
- High heating rates decrease burst strains
  - NUREG/CR-0344 tests
- High external pressure in PWRs and HZP BWRs prevent ballooning for low burnup fuel
  - Halden IFA-613 show clad collapse during post-DNB operation with coolant overpressure
  - CABRI and NSRR test results (2008-2012) will provide information on the role of fission gas release on clad ballooning

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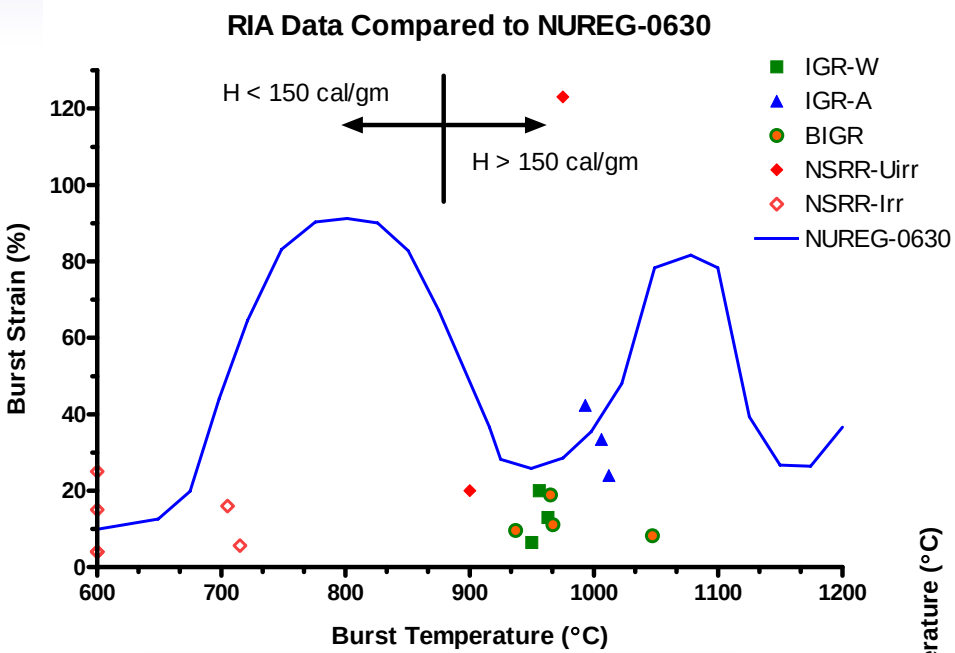
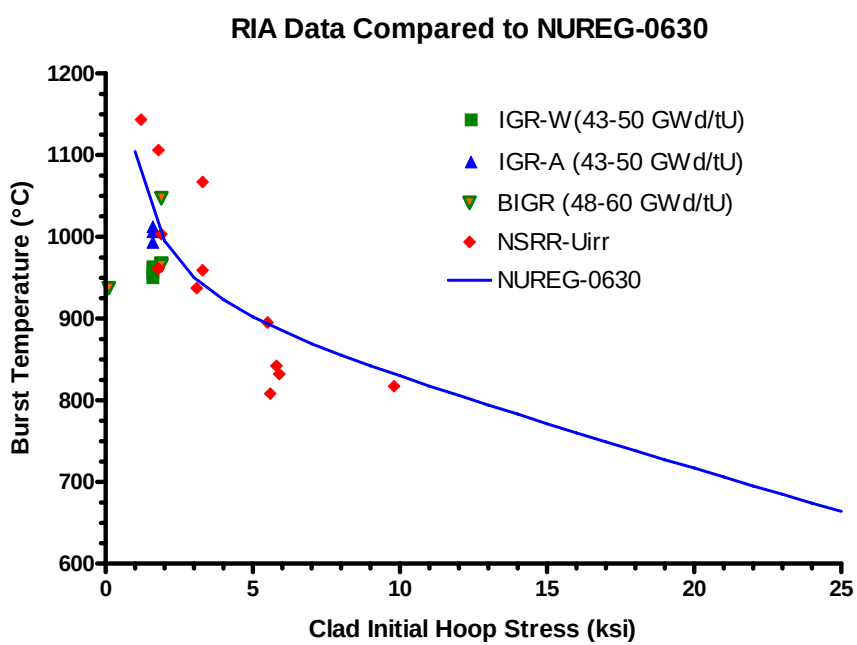
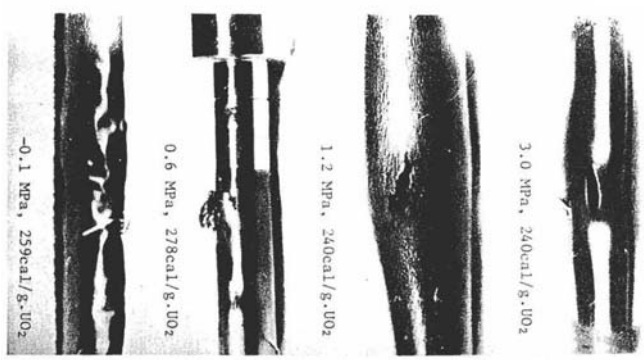
Low Burst Strain from RIA Test Data



Burst predominately in α+β temperature regime





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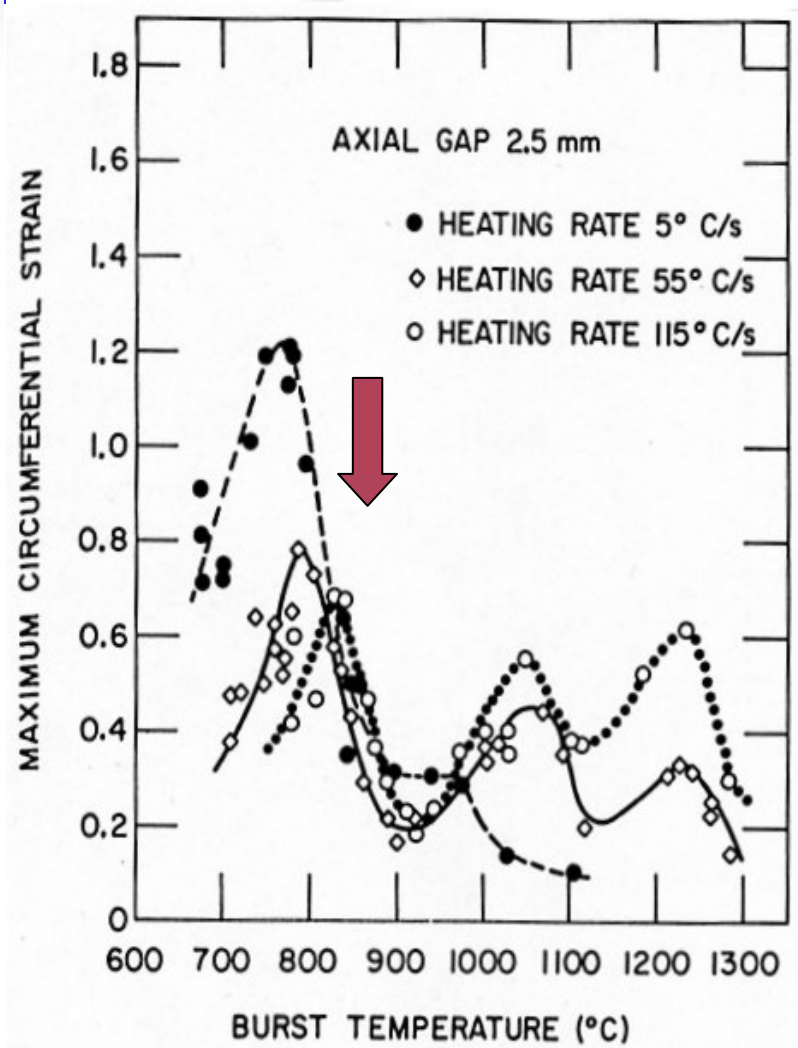
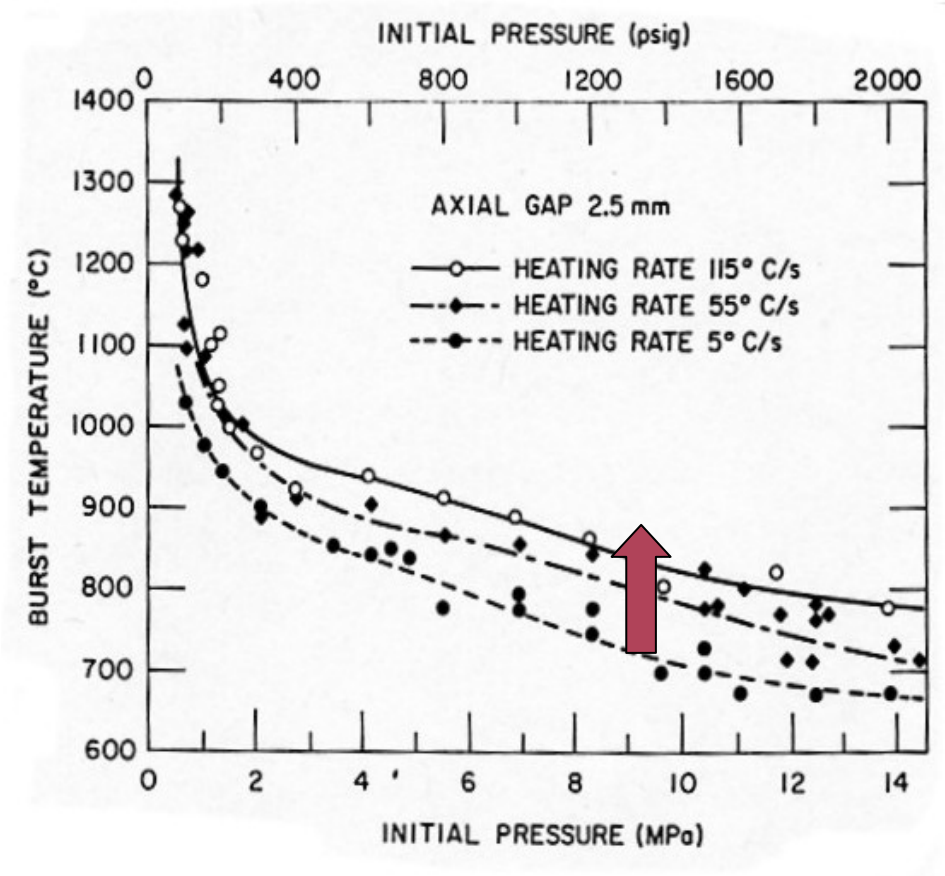
Decrease Burst Strain and Increase Burst Temperature for Fast Heating Rates



Ref: Chung and Kassner, NUREG/CR-0344



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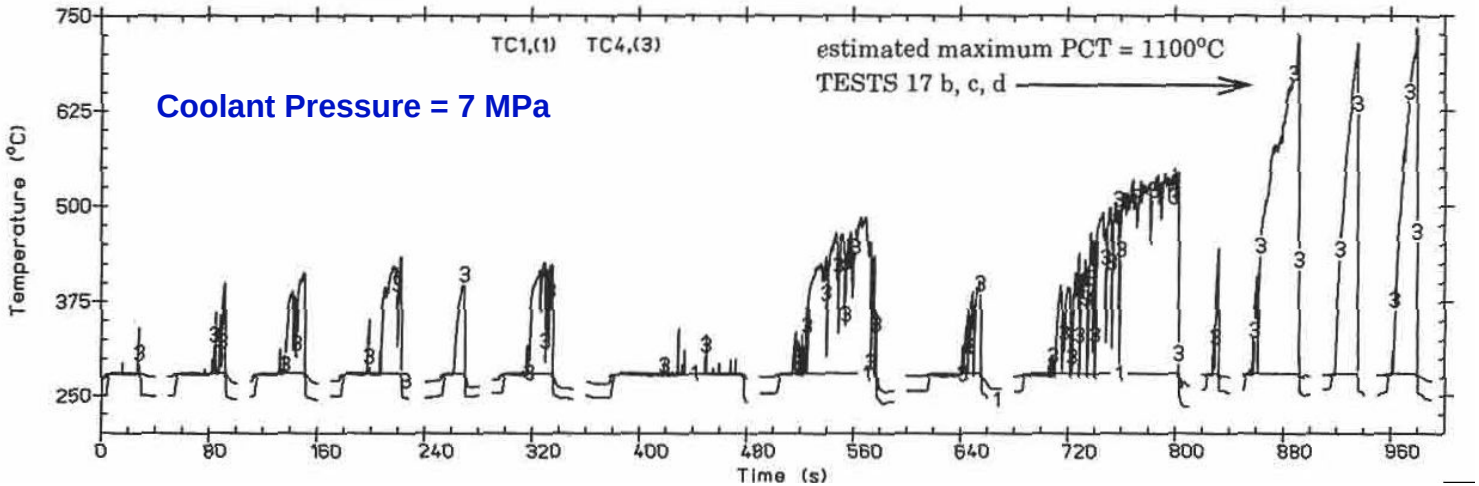
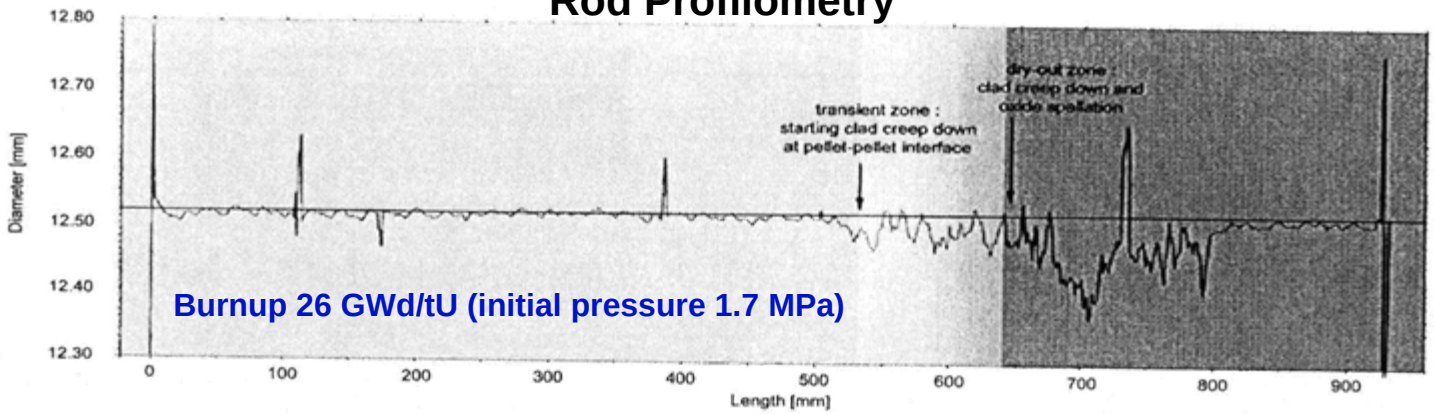
Clad Collapse during Post-DNB Conditions

Halden IFA-613 Dryout Experiment



Rod Profilometry



Diameter scan at 0 degree orientation

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Potential Flow Blockage from Clad Ballooning

- Limited flow channel reduction compared to LOCA
  - Less fuel assemblies will experience ballooning
  - Lower cladding strains results in less channel blockage

- Full flow and coolant volume available to cool deformed fuel rods
  - Maintain heat transfer in upper region of the assembly

Flow Blockage in RIA is Bounded by LOCA Conditions

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Flow Blockage from Fragmented Fuel Transport

- Similar scenarios addressed in BWR and PWR LOCA Long-term Cooling Assessments
  - BWR lower tie plate clogging tests
  - PWR sump clogging tests (W presentation)
  - Amount of material is small compared to the material expelled during a LOCA (fuel + sump debris)

Possible to demonstrate that flow blockage from fragmented fuel is bounded by LOCA

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Other Consequences from Fragmented Fuel Transport

- Very low probability for a critical configuration and rubble bed overheating
  - Limited amount of material to form large rubble bed
  - Dispersed material will have low reactivity worth due to depletion of fissile atoms and fission products
  - Full flow conditions limits accumulation fuel material

Possible to demonstrate that consequences of fragmented fuel transport is bounded by LOCA

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Industry Approach to Short-Term Coolability BWR CRDA

- Pulse characteristics in BWR CRDA will mitigate fuel dispersal upon failure
  - Pulse width > 20 ms even at the highest rod worths
  - Significant fraction of deposited energy is in delayed power tail – mode of failure DNB
  - No need to calculate mechanical energy generation from fuel dispersal

- Mechanical energy generation from clad ballooning failure
  - Develop approach to calculate pressure pulse generation from rod pressure release upon failure

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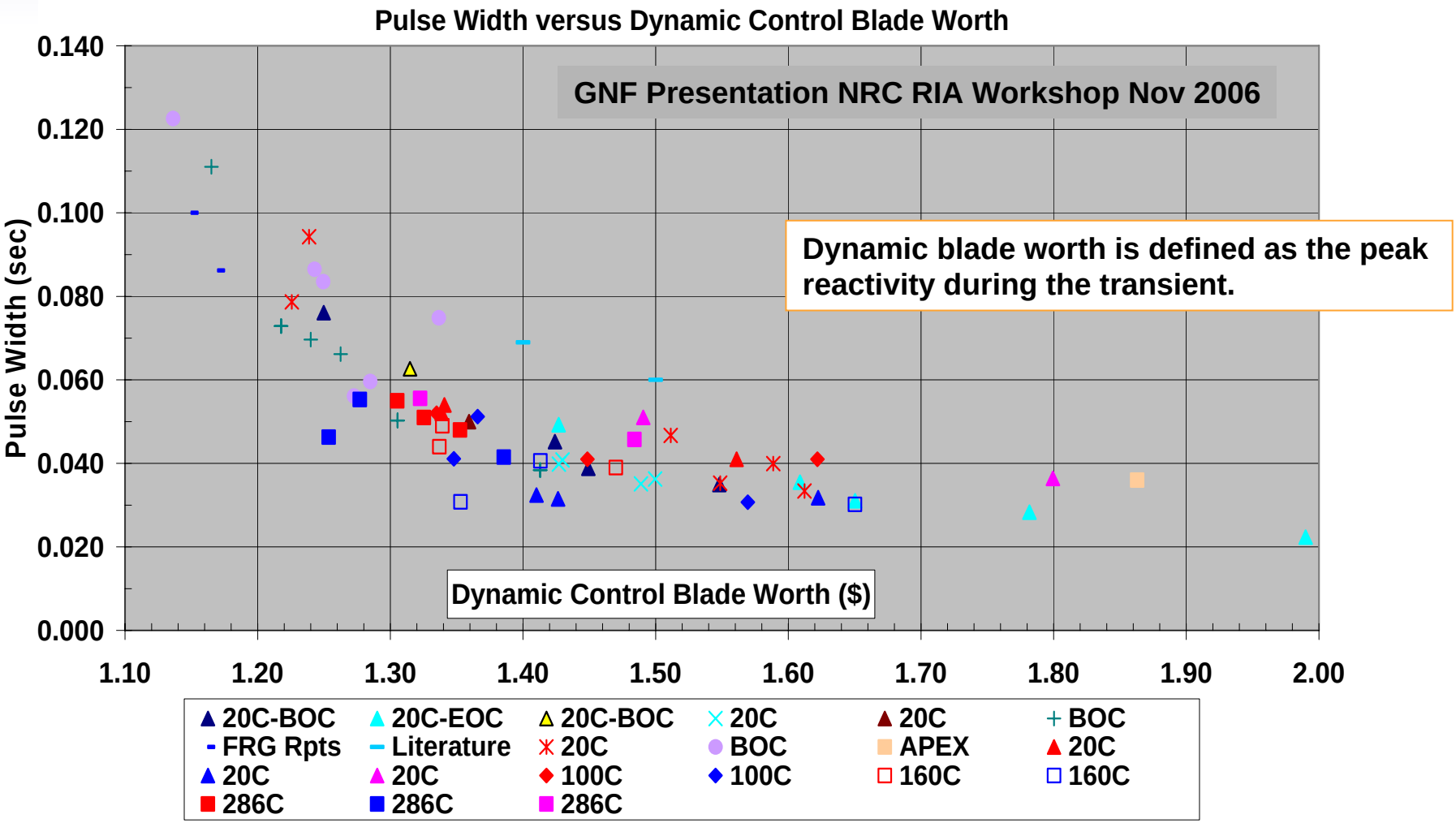
BWR Pulse Widths versus Control Blade Worth



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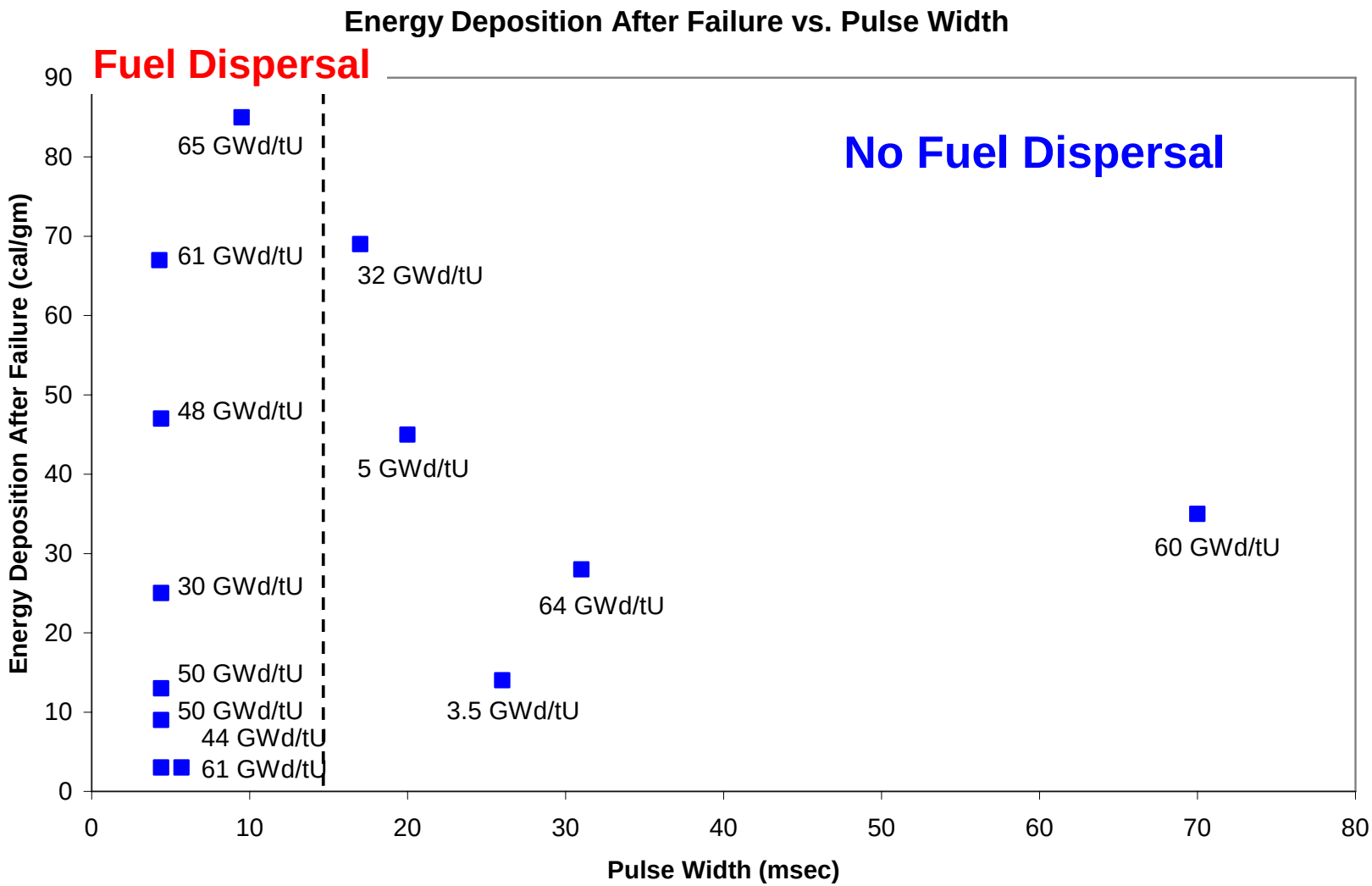
Effect of Pulse Width on UO_2 Fuel Dispersal



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Industry Approach to Short-Term Coolability PWR REA

- Estimate consequences of fuel dispersal for PWR REA
  - Narrow pulse widths may not preclude fuel dispersal
  - Develop approach to calculate mass and energy of dispersed fuel
  - Develop approach to calculate pressure pulse generation and structural response of core internals

- Mechanical energy generation from clad ballooning failure
  - Develop approach to calculate pressure pulse generation from rod pressure release upon failure

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Assessment of Fuel Dispersal Consequences

- Estimate mass and energy of dispersed fuel during an RIA event
  - Use 3-dimensional distribution of core power during rod ejection/rod drop accident
  - Function of maximum fuel enthalpy and the failure threshold

- Estimate mechanical energy generation and impact on reactor coolant system during an RIA event
  - Pressure and water hammer from fuel-coolant interaction leading to destructive forces on the fuel assembly, core components, and the reactor pressure vessel

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Estimate the Amount and Energy of Dispersed Fuel

- Use results from 3-D neutron kinetics analysis and core burnup distribution to identify all failed nodes in core
  - Assume fuel enthalpy is proportional to power
  - Correlate local enthalpy, assembly/rod average burnup and postulated failure threshold to identify failed nodes

- Estimate amount of fuel dispersed and the thermal energy
  - Function of maximum allowable fuel enthalpy and failure threshold
  - Function of key assumptions related to the fuel dispersal kinetics

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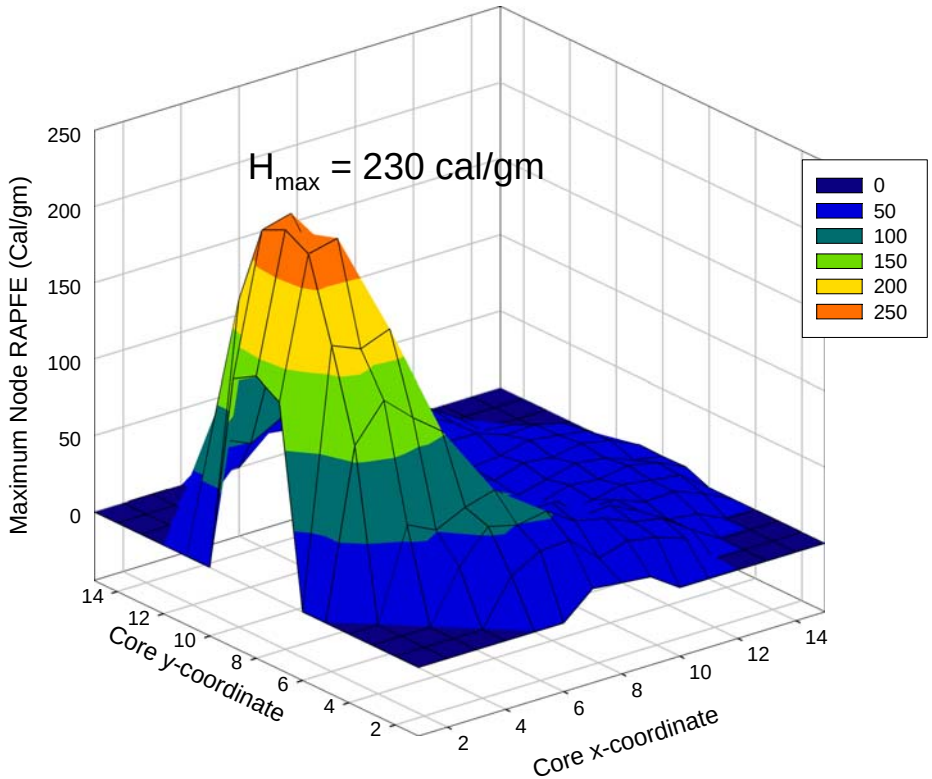
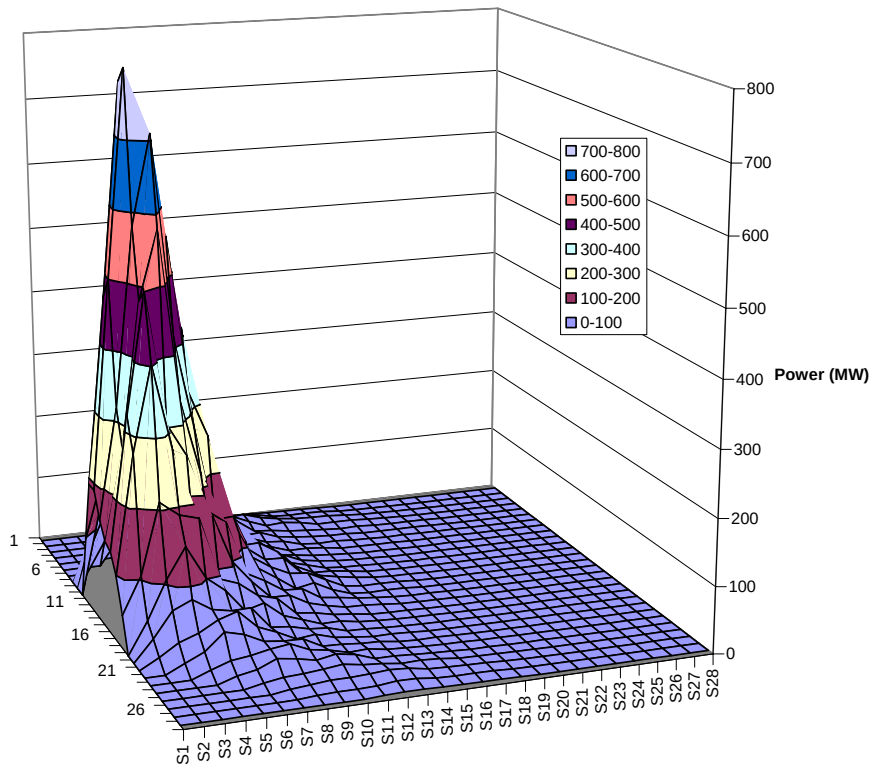
Core Power Distribution

Core Enthalpy Distribution for a
PWR Control Rod Ejection



Core Power Distribution for a
BWR Control Rod Drop Accident



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Example of Fuel Dispersal Calculation for PWR Rod Ejection Accident

- Core Power and Burnup Distribution from Westinghouse 3-D Analysis
  - Radial (assembly) and axial relative power distribution
  - Assembly burnup distribution to determine failure threshold for each assembly

- Fuel Enthalpy Distribution Throughout the Core
  - Combine core radial peaking factor and axial peaking factor and multiply by maximum radial average peak enthalpy
    - Use three different max values - 230, 200, and 170 cal/gm
    - Hypothetical ejected rod worth values to reach maximum allowable enthalpy levels
  - Assume axial and radial power distribution is not function of maximum enthalpy (reactivity insertion)

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Fuel Dispersal Kinetics Assumptions

- Estimated mass and energy of dispersed fuel using two methods
  - All failed nodes disperse fuel at maximum fuel enthalpy
  - Assemblies above 30 GWd/tU disperse fuel at failure enthalpy (only nodes that fail by PCMI)

- 20% of fuel in qualifying nodes dispersed into coolant
  - Upper limit of fuel dispersal amounts in NSRR tests without end/bending effects

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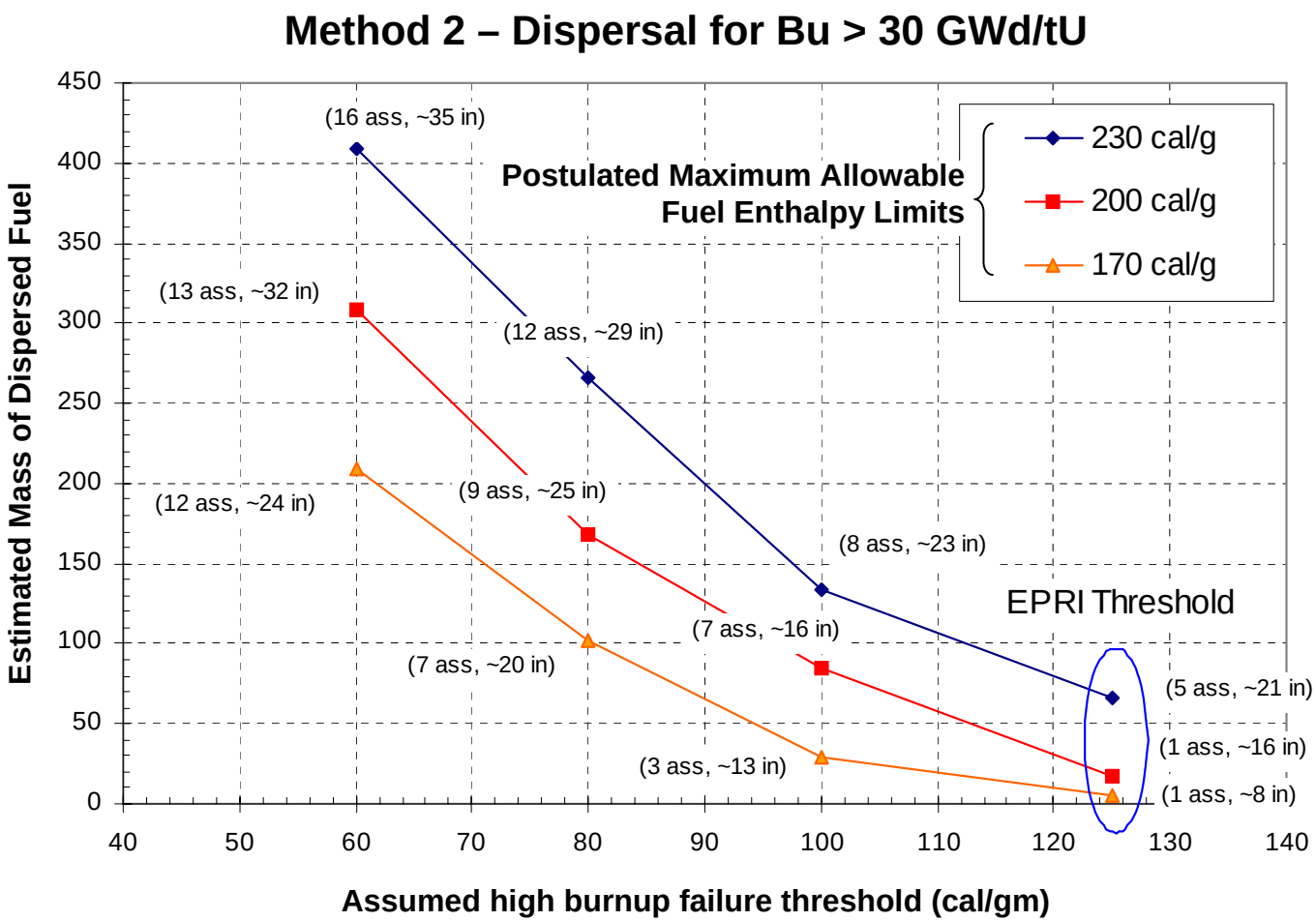
Mass of Fuel Dispersal as Function of Failure Threshold and Maximum Allowable Enthalpy



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Fuel Dispersal Consequences - Mechanical Energy Generation

- Previous analysis results sensitive to assumed thermal equilibration time between fuel particles and coolant
  - Pressure pulse magnitude varied by factor of 10 for thermal equilibration times between 1 and 100 ms

- Modeling required to improve energy transfer kinetics between dispersed fuel and coolant
  - Coherency of dispersed material
  - Particle size distribution effect
  - Coolant voidage

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Several Methods to Assess RCS Integrity

- Use maximum allowable pressure (120% of design pressure)
  - Evaluate transient pressure pulse using static pressure limit

- Use maximum absorbable energy of the reactor vessel (energy needed to yield the reactor vessel)
  - Japanese and EdF approach
  - No consideration give to damage of internal structures

- Assess damage to reactor internals (core barrel, fuel assembly, etc.)
  - Local pressure and flow velocities used to calculate structural response
  - Need structural limits to assess impact on coolability

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Summary

- Experimental data and evaluations support maximum enthalpy limit well above failure threshold
- Consequences of fuel failure during RIA on long-term cooling bounded by LOCA event
- Short-term consequences of failure and fuel material dispersal can be addressed in coolability limit
- Industry looks forward to working with the staff on resolution of the coolability issues for RIA

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