Industry Information to Support Interim RIA Criteria

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Public Workshop on Interim RIA Criteria
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Outline

- Support for Separate Core Coolability Limit
- Support for Fuel Rod Failure Threshold for BWR CRDA
- Support for Fuel Rod Failure Threshold for PWR REA

Support for Separate Core Coolability Limit

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Industry Position on Coolability Limit

- RIA is a Low Probability, Limited Core Event
  - Very unlikely to reach limiting conditions required for prompt criticality
  - Reactivity excursion is limited to small region of the core adjacent to the ejected/dropped control assembly
- Safety limits should be established commensurate with the risks of the event
  - Precluding fuel failures is not consistent with a Category IV accident
- Maintain separate fuel failure and coolability criteria
  - Collapsing coolability limit to prevent failures is very restrictive for modern core designs
  - Sufficient data and analyses show that fuel rod failure does not necessarily lead to loss of coolable core geometry
  - Consistent with ACRS Fuels subcommittee feedback

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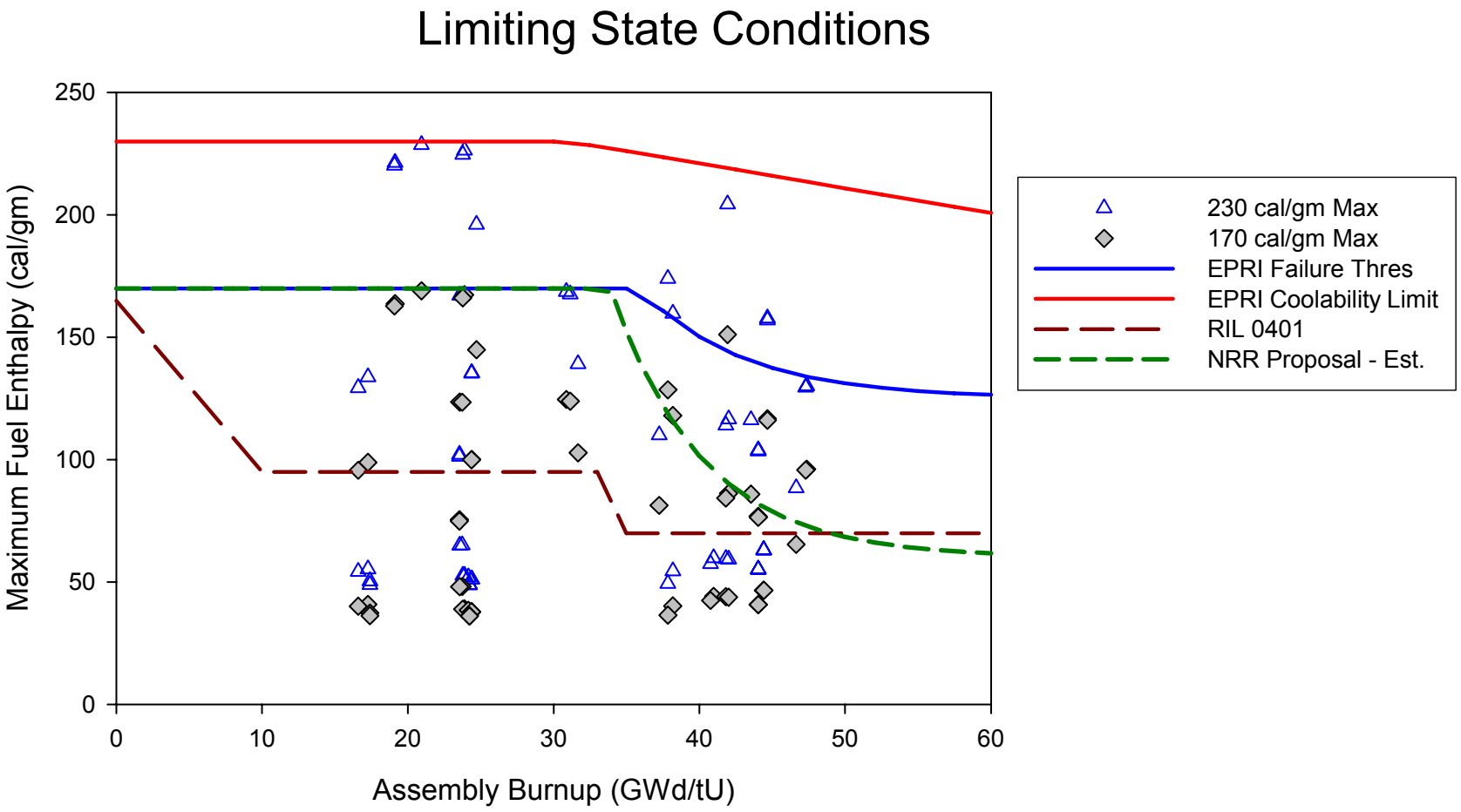
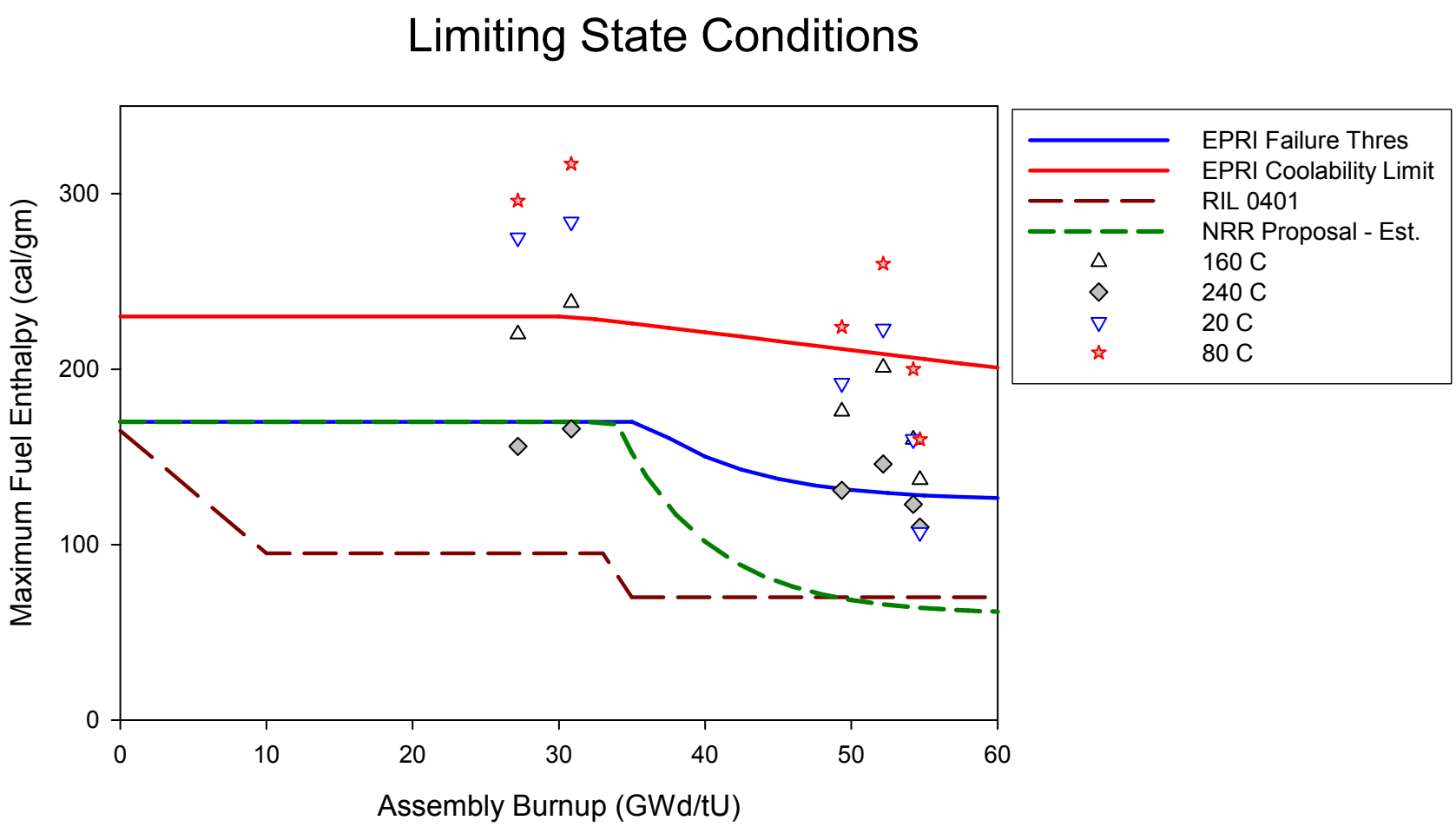
Collapsing Coolability Limit is Overly Restrictive

- Low coolability limit at mid to high burnup is overly restrictive
  - Modern core loading designs lead to high enthalpy (80-90% of maximum enthalpy) in limited number of high burnup assemblies
  - Having higher enthalpy limit at low burnup does not help
- Significant impact on core design without improvement in safety
  - Impacts core designs by limiting rod worths or requiring stricter requirements on locations for higher burnup assemblies
  - Could lead to high leakage cores → higher vessel fluences
  - Move back to yearly cycles → decreased capacity factors

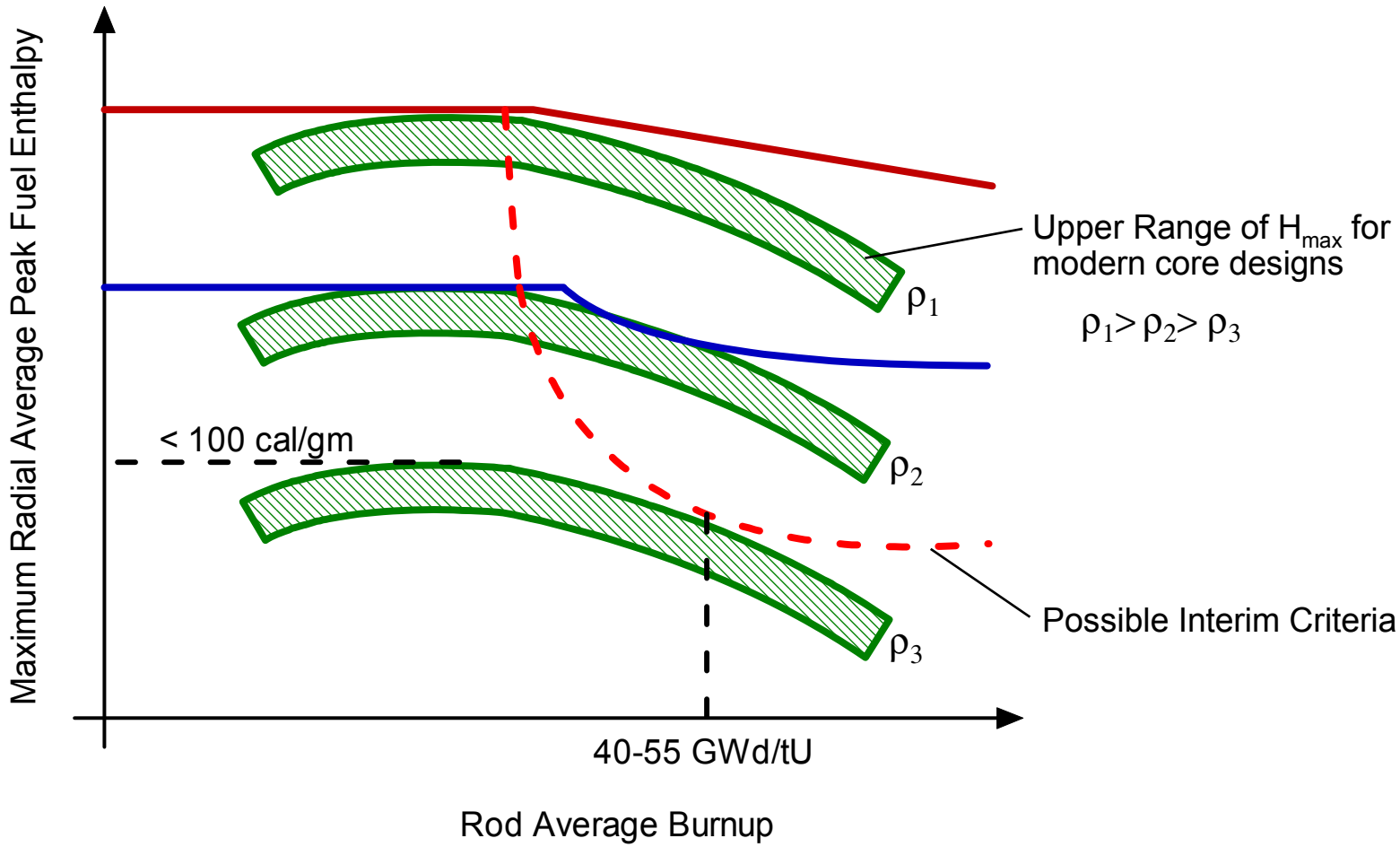
Fuel Enthalpy as Function of Burnup - PWR



Fuel Enthalpy as Function of Burnup - BWR



Impact of RIA Criteria on Core Design



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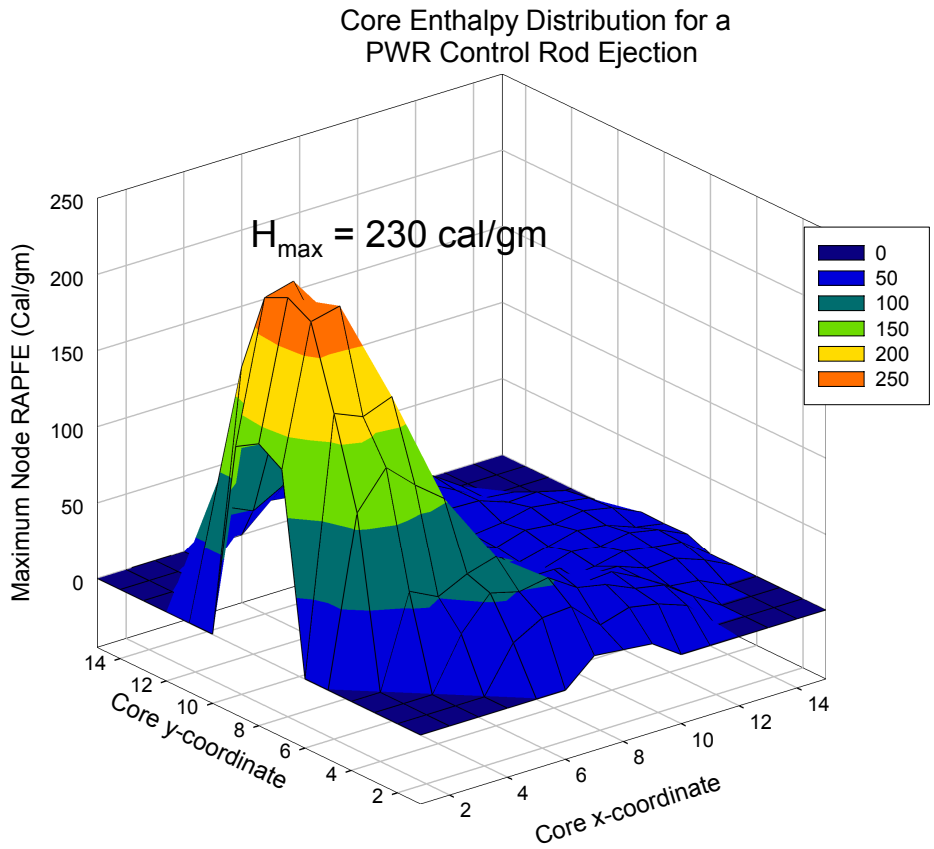
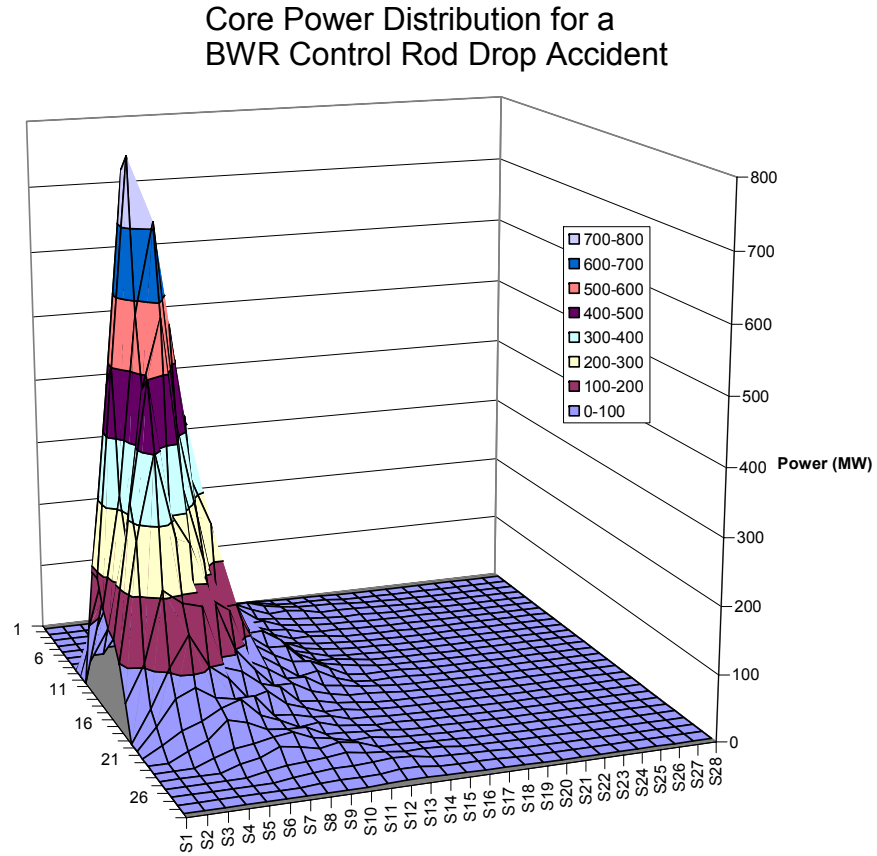
Failure ≠ Loss of Coolable Core Geometry

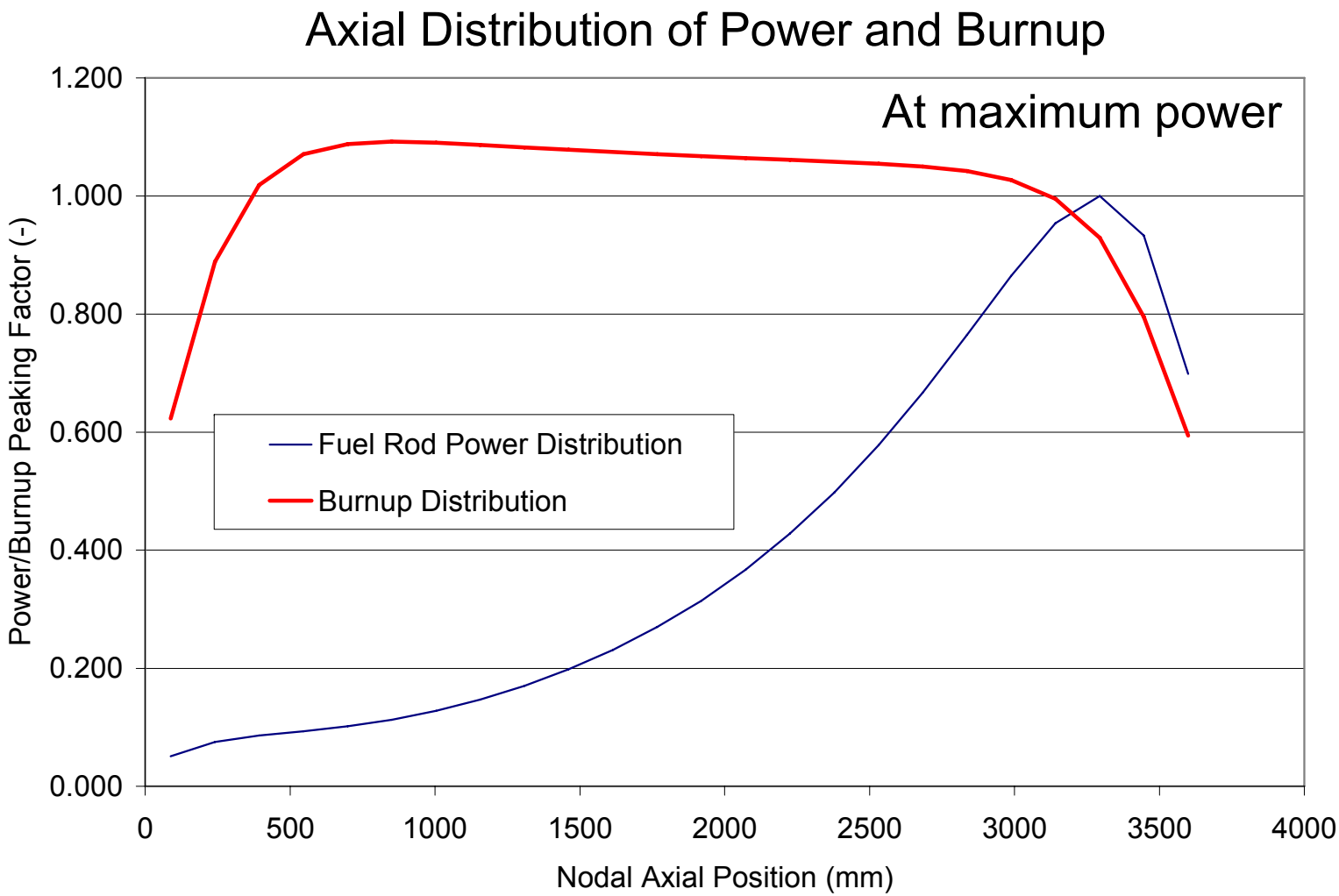
- Cladding failure and potential fuel dispersal are limited
  - Limited to local region adjacent to ejected/dropped rod
  - Axial distribution of energy deposition limits amount of affected fuel to approximately 1 grid span or less
  - Pellet radial power profile limits amount of affected pellet to < 20%
  - Combining all factor → Less than 1% of the fuel is affected by the RIA power transient
- Not all Cladding Failures Lead to Pellet Material Dispersal
  - Experimental data show dispersal kinetics depend on pulse width, burnup, enthalpy level, failure mode, etc.
- Consequences of Potential Fuel Dispersal are Limited
  - Fuel rod failures are not simultaneous
    - » Lack of coherency between different fuel dispersal events dampens FCI energetics
  - Size of dispersed solid fuel particles delays energy transfer to coolant

Core Power Distribution

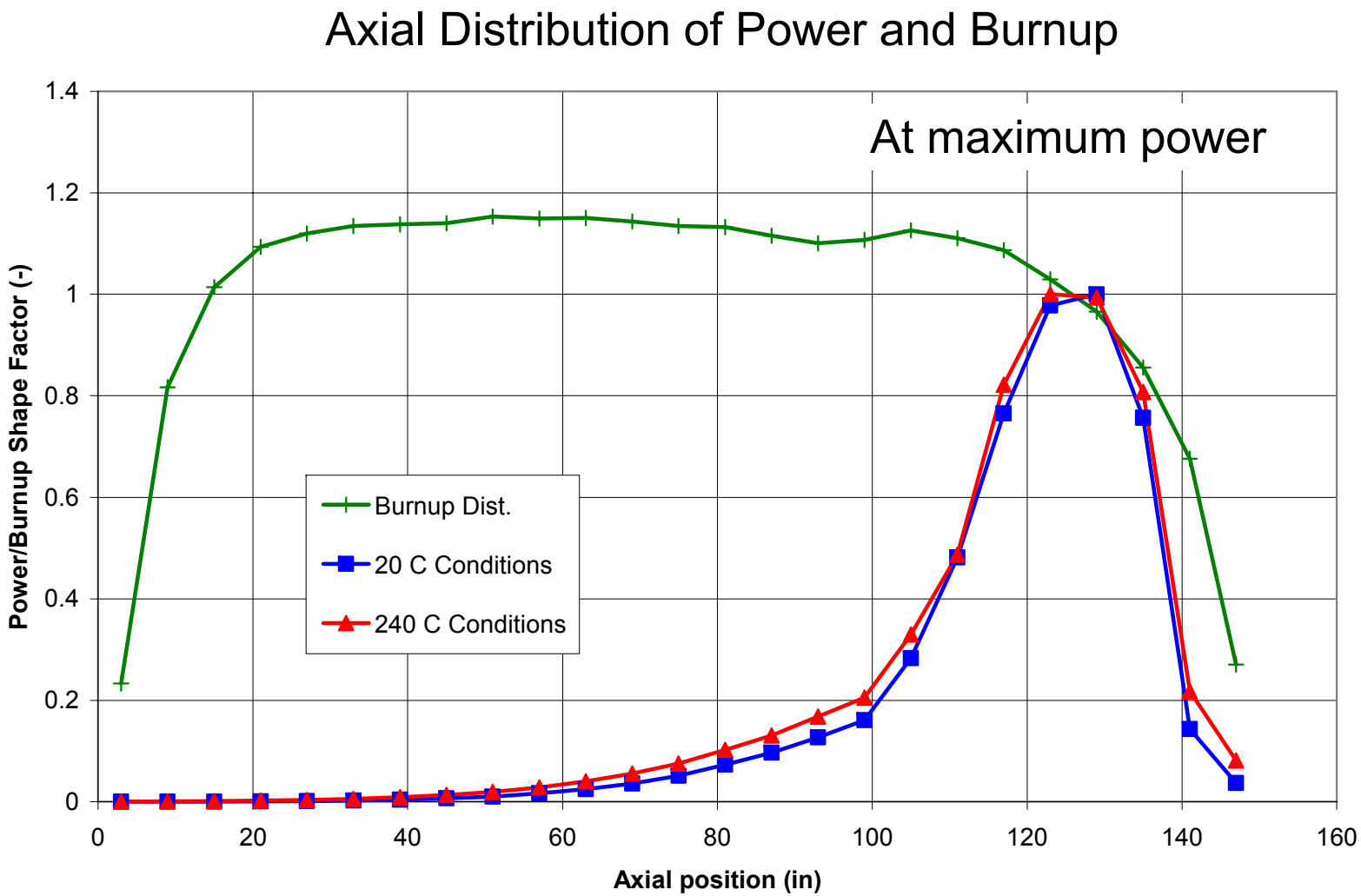




PWR Control Rod Ejection

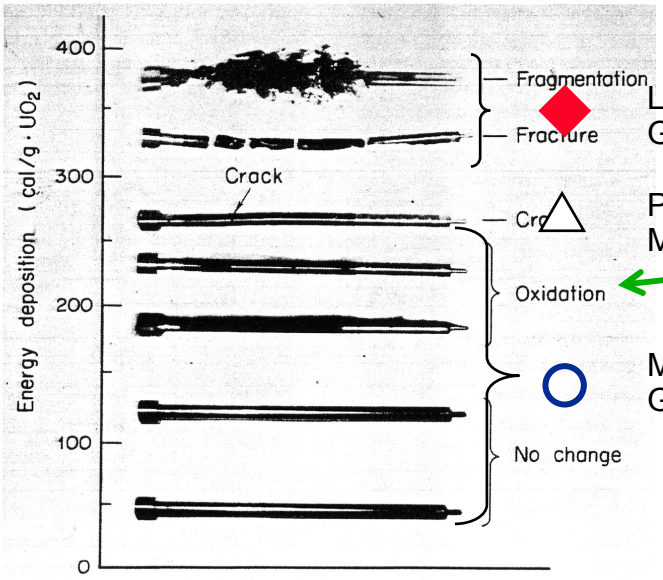


BWR Rod Drop Accident



Post-Test Condition with Fuel Dispersal

Unirradiated Tests in NSRR [2]



Loss of Rod Geometry

Partial Clad Melting

Maintain Rod Geometry

Bu = 30 GWd/tU [1]

H_{max} = 220 cal/gm

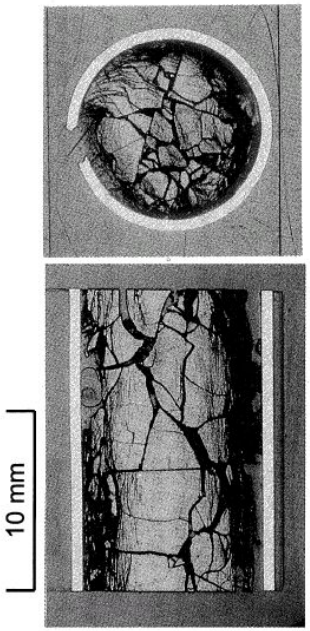


Photo. 1 Appearance of JMH-5 test fuel rod

Photo. 2 Metallographs of JMH-5 test fuel

~20% fuel dispersal

Irradiation has very little impact on fuel rod appearance after high energy deposition

2. Ishikawa, M, and Shiozawa, S., "A Study of Fuel Behavior Under Reactivity Initiated Accident Conditions – Review," Journal of Nuclear Materials 95, pp. 1-30, 1980.

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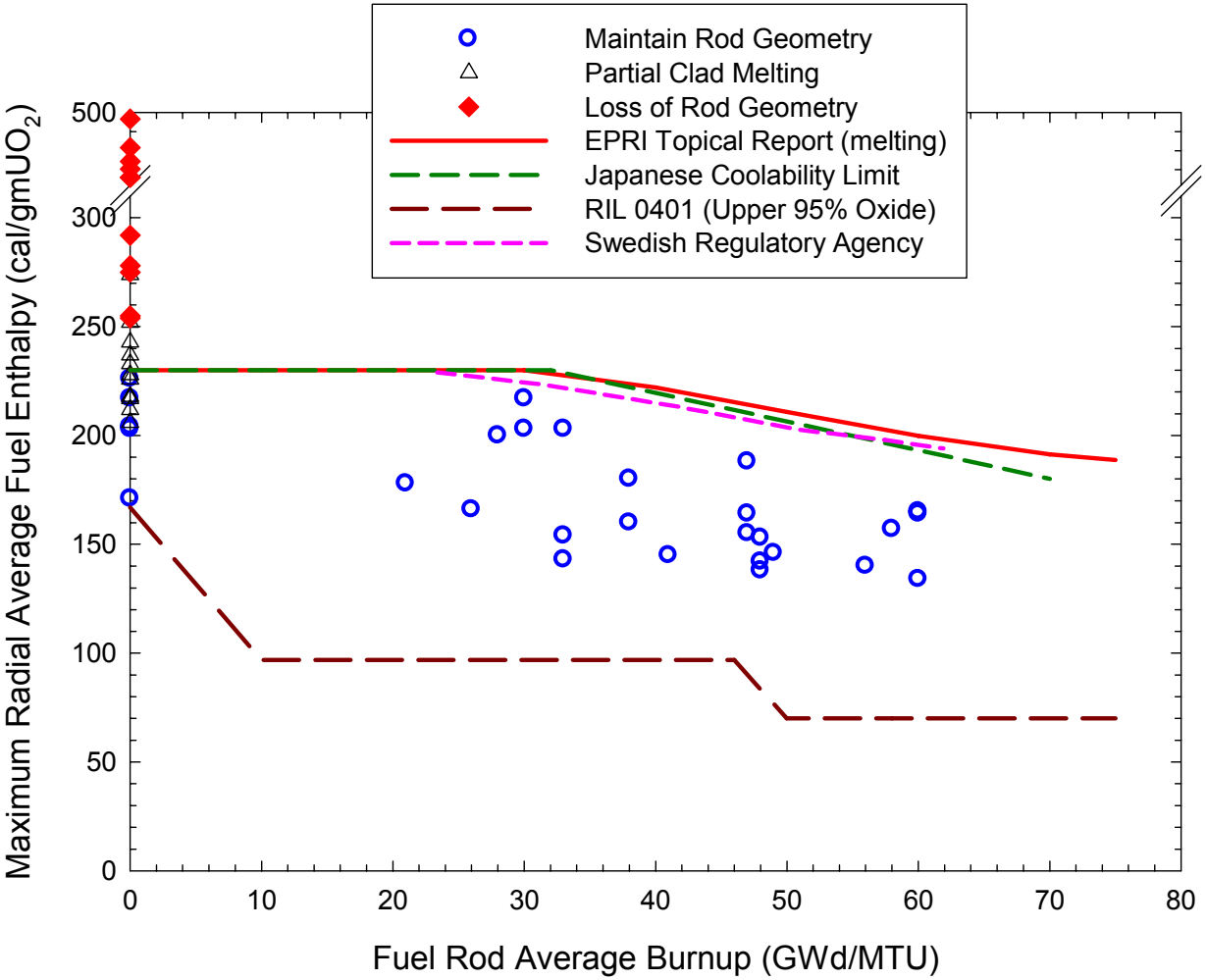
Maintain Separate Failure and Coolability Criteria

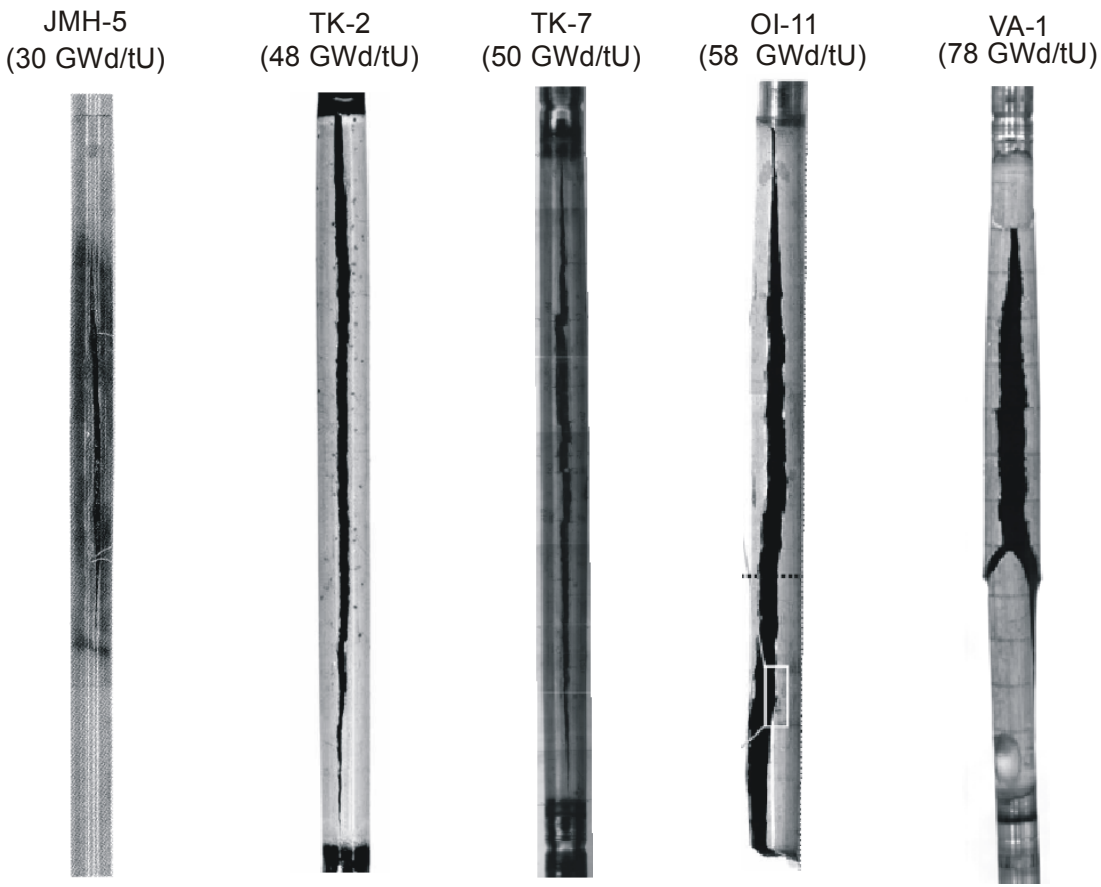
- Experimental Observations
  - Majority of failures above RIL-0401 limit maintained rod geometry
  - Consequences of fuel dispersal did not lead to damaging pressure pulses or loss of rod geometry
- Analytical Evaluations
  - Pressure pulse generation from dispersal of non-molten material is within the reactor pressure vessel limits (RETRAN analysis, others)
- Other Assessments Support Separate Criteria
  - Nuclear Safety Commission of Japan (NSCJ), Swedish Safety Authority (SKI), Switzerland (HSK), others
  - These other limits are a function of burnup
- Sufficient data and analysis exists to justify separation between failure threshold and coolability limit

Experimental Results Above RIL 0401



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

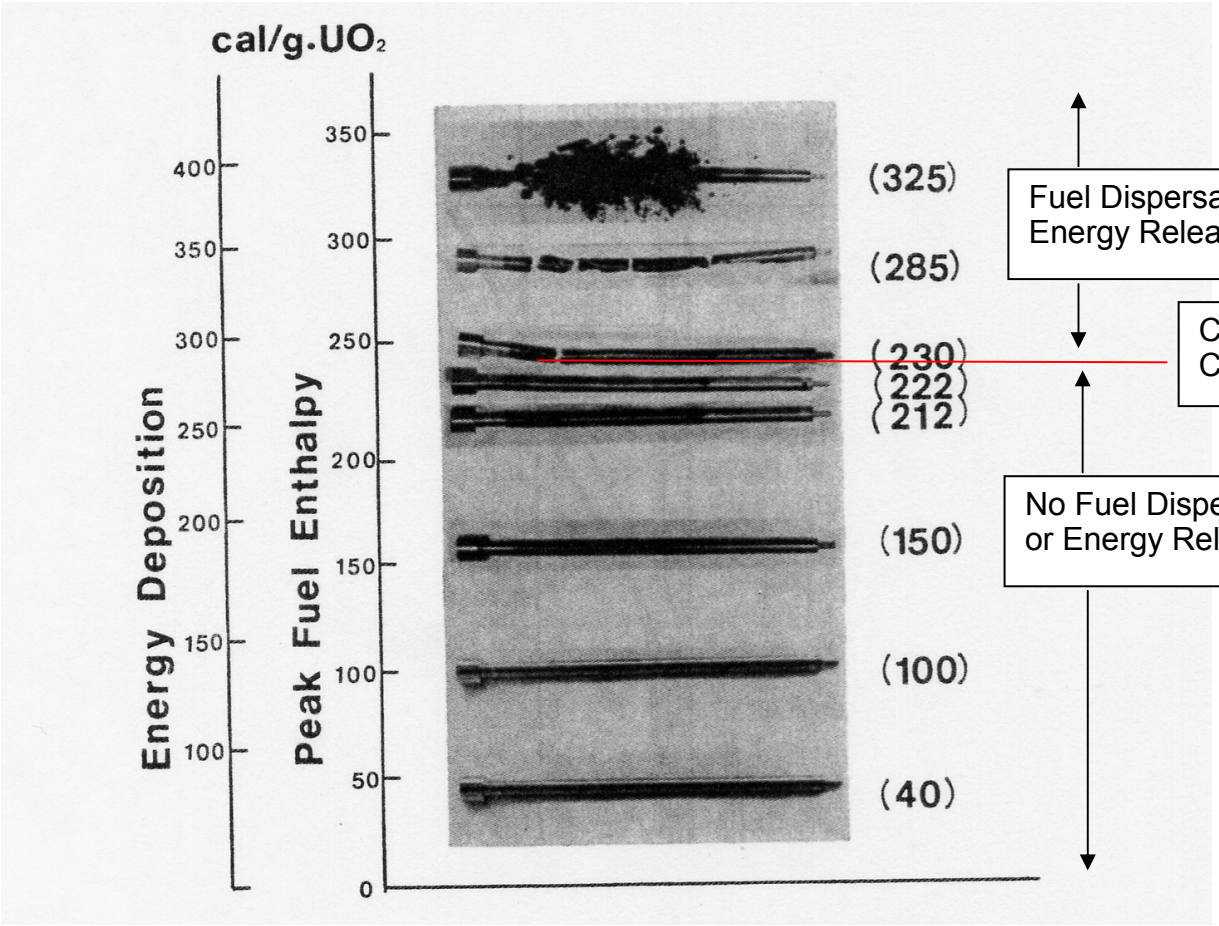
NSRR Experiments
Pulse widths: ~4 ms
Rod Length: 5 to 6 in
Uniform Axial Power



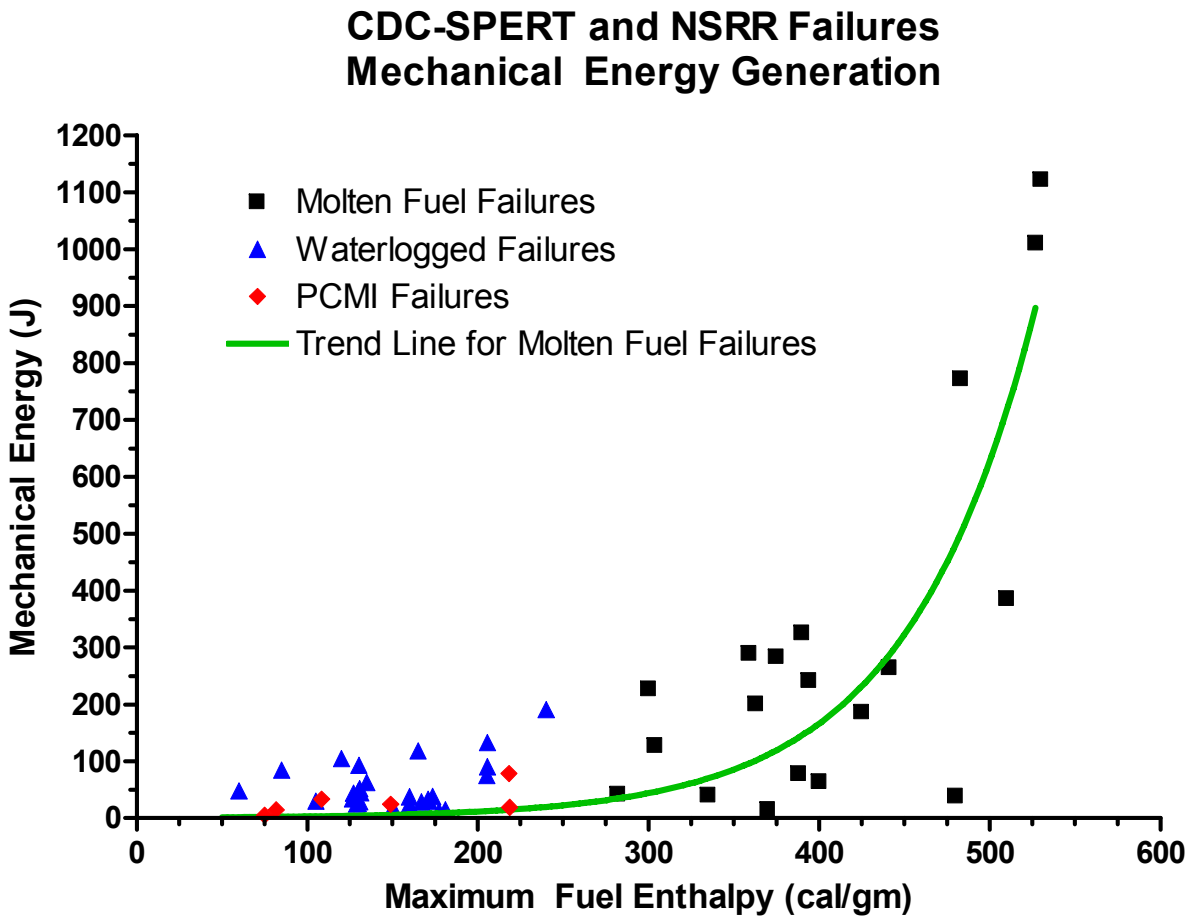
220 cal/gm | 107 cal/gm | 95 cal/gm | 157 cal/gm | 127 cal/gm

Maximum Radial Average Peak Fuel Enthalpy

Appearance of Unirradiated Test Rods After RIA Experiments

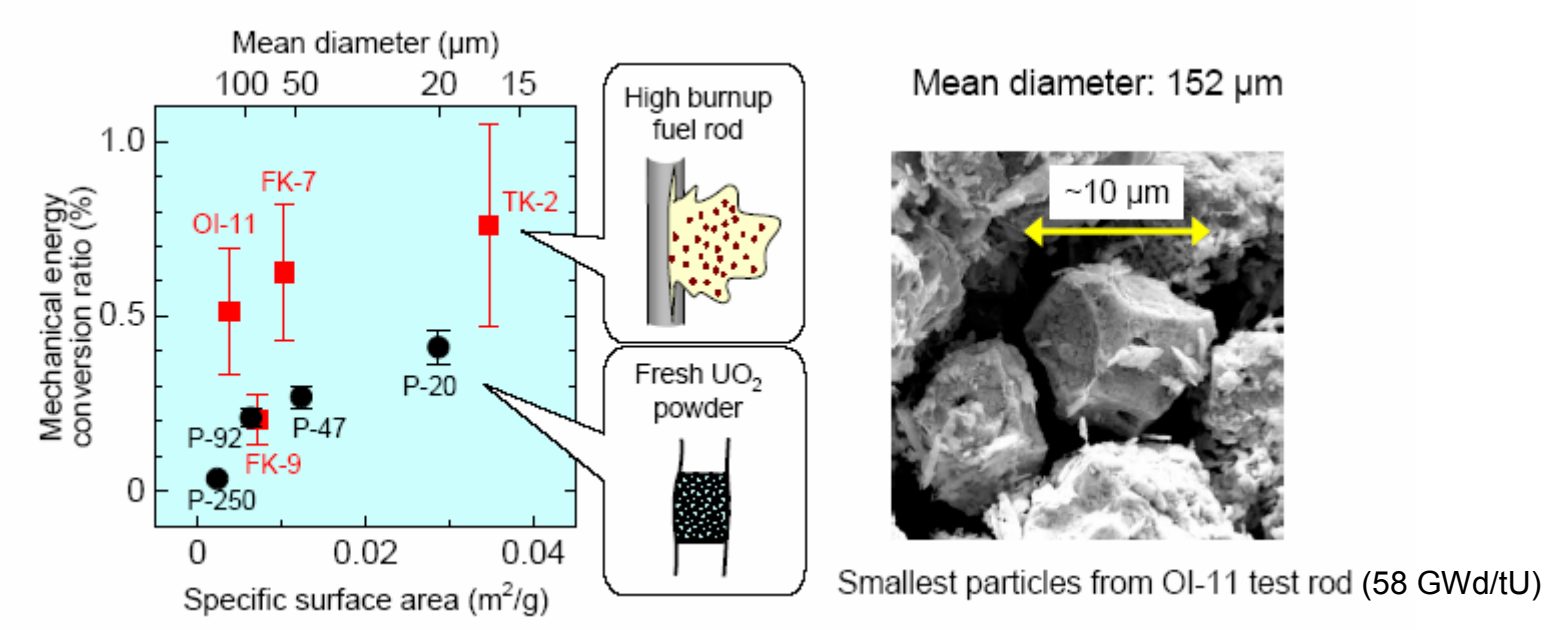


Mechanical Energy Generation after Cladding Failure



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

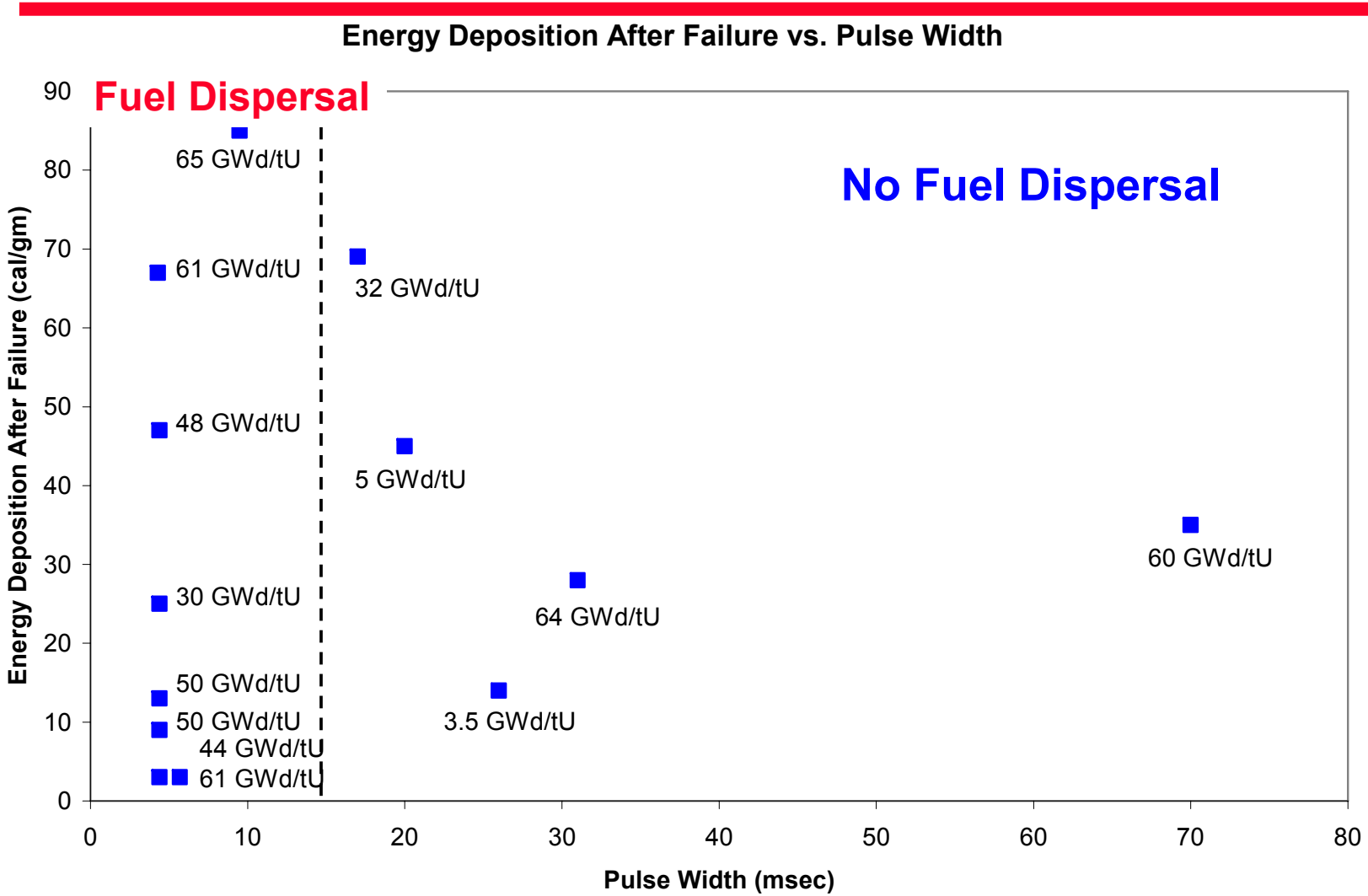
Particle Size in Dispersed Fuel



Mean Particle Size:

- 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

Effect of Pulse Width on UO_2 Fuel Dispersal



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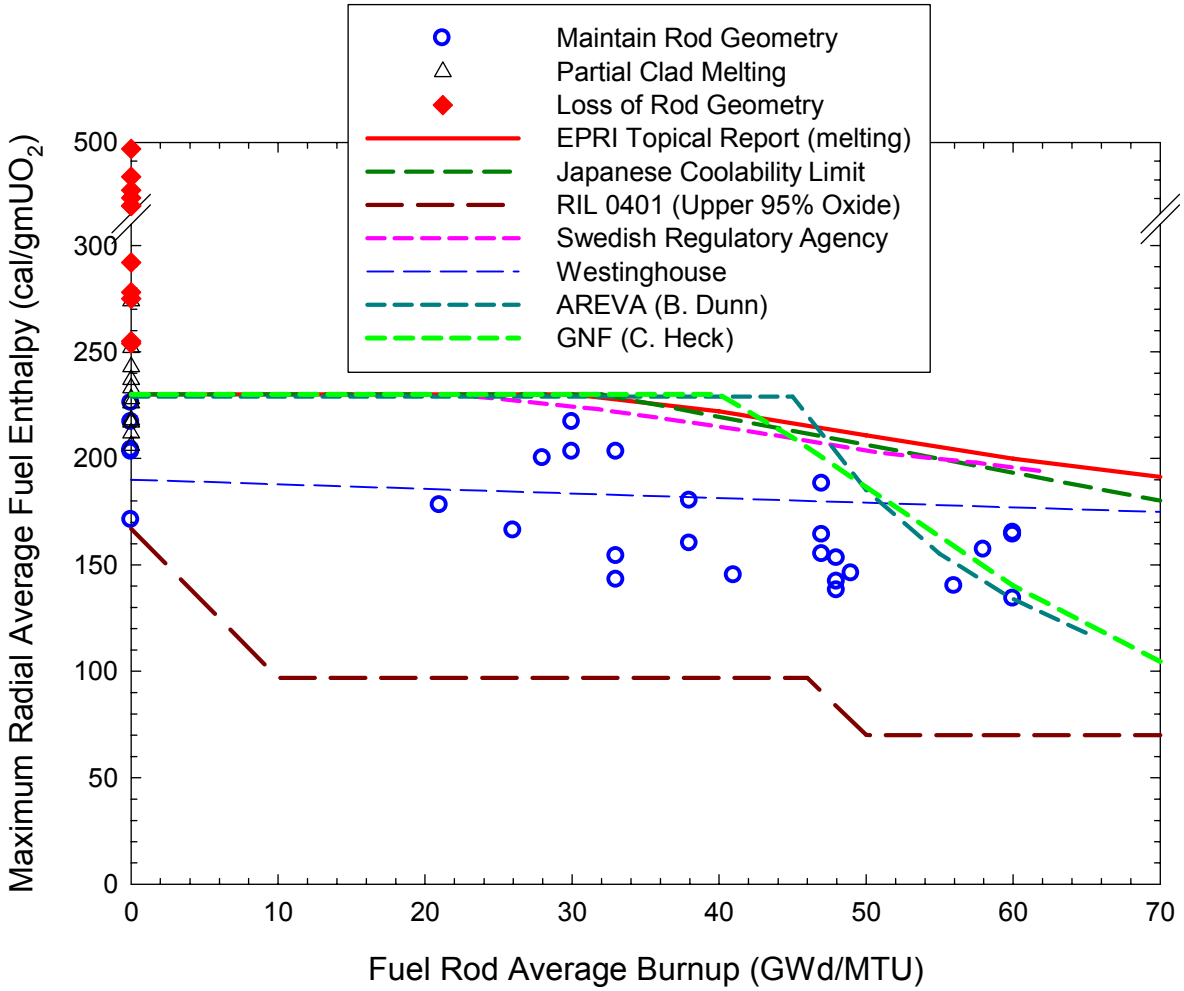
Approach to Develop Core Coolability Criteria

- Develop interim coolability limit based on restricting amount of potential fuel dispersal (as a means to limit consequences)
  - NRC-RES position - No fuel failures for irradiated fuel
  - Industry interim position –
    - » Translate currently accepted low exposure response to equivalent energy at higher exposure based on pellet condition

- Possible methods to develop coolability limit based on limiting the consequences of fuel dispersal (considerations for final rule)
  - Consider consequences of
    - » potential pressure pulse generation following fuel dispersal
    - » potential fuel sediment bed forming and overheating

Industry Concepts



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NSJC Assessment of RIA Limits

- Evaluation Guideline for Reactivity Initiated Event - originally issued in 1984
  - Failure threshold as function of Internal Pressure
  - Burnup effect acknowledged based on early SPERT tests
  - Coolability limit to prevent pressure pulse generation from molten fuel dispersal
  - Included consideration for mechanical energy release from waterlogged rods
- Update Issued in 1998 for High Burnup Fuel Application
  - Added failure threshold as function of burnup based on NSRR database
  - Burnup dependent coolability limit to account for burnup impact on fuel melting temperature
  - Added PCMI failures to mechanical energy release after failure
  - Assessment of coolability of dispersed fuel sediment
  - Assessment of fission product release for high burnup fuel

BWR Failure Threshold Support

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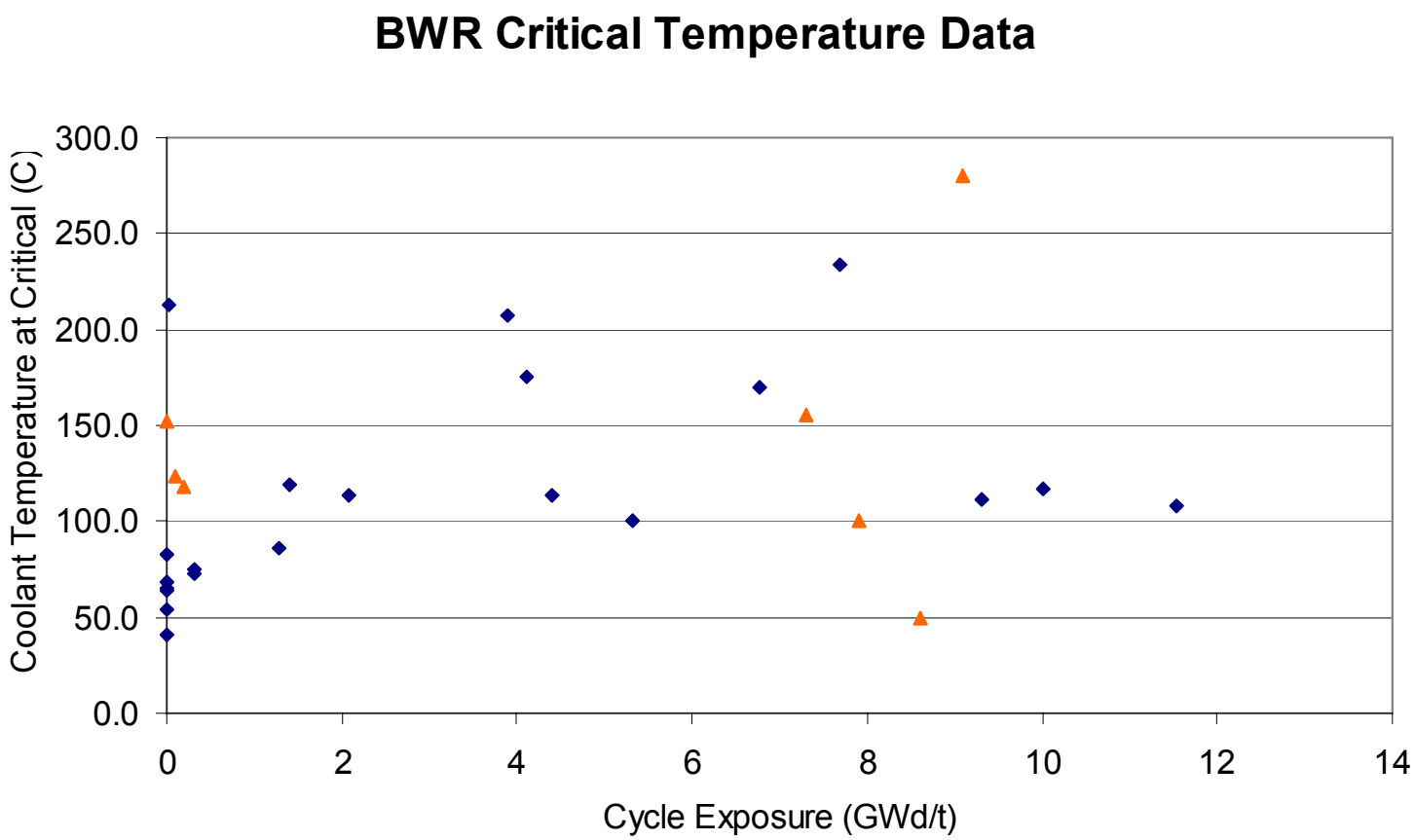
Failure Threshold Development for BWR CRDA

- Initial focus on failure threshold primarily for PWR cladding
  - Most experiments in CABRI and NSRR on PWR test rods
  - Mechanical properties data and corrosion behavior from Zr-4 cladding
  - Pulse shape characteristic of PWR rod ejection accident with 100% deposited energy as prompt (gaussian)
  - Applies to initial coolant temperatures greater than ~280ºC (HZP)

- BWR-specific Issues in Control Rod Drop Accident
  - Accident can initiate at temperatures well below 280ºC
  - Power pulse shapes non-gaussian, especially at low temperature with significant fraction of non-prompt energy deposition
  - Mechanical performance of irradiated BWR cladding at low temperature
  - Both PCMI and ballooning failure modes are possible

BWR Criticality Conditions
Moderator Temperature During Startup



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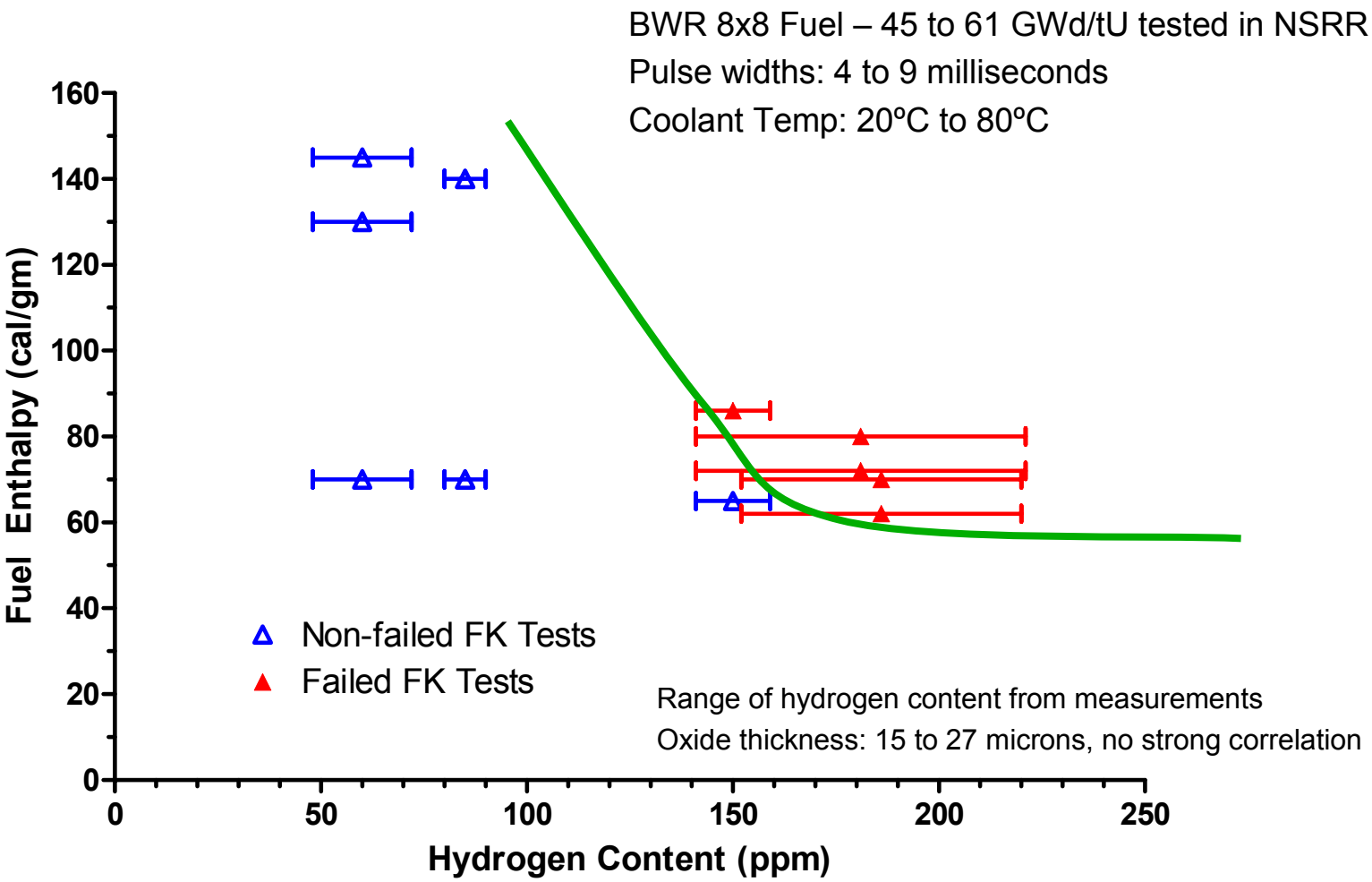
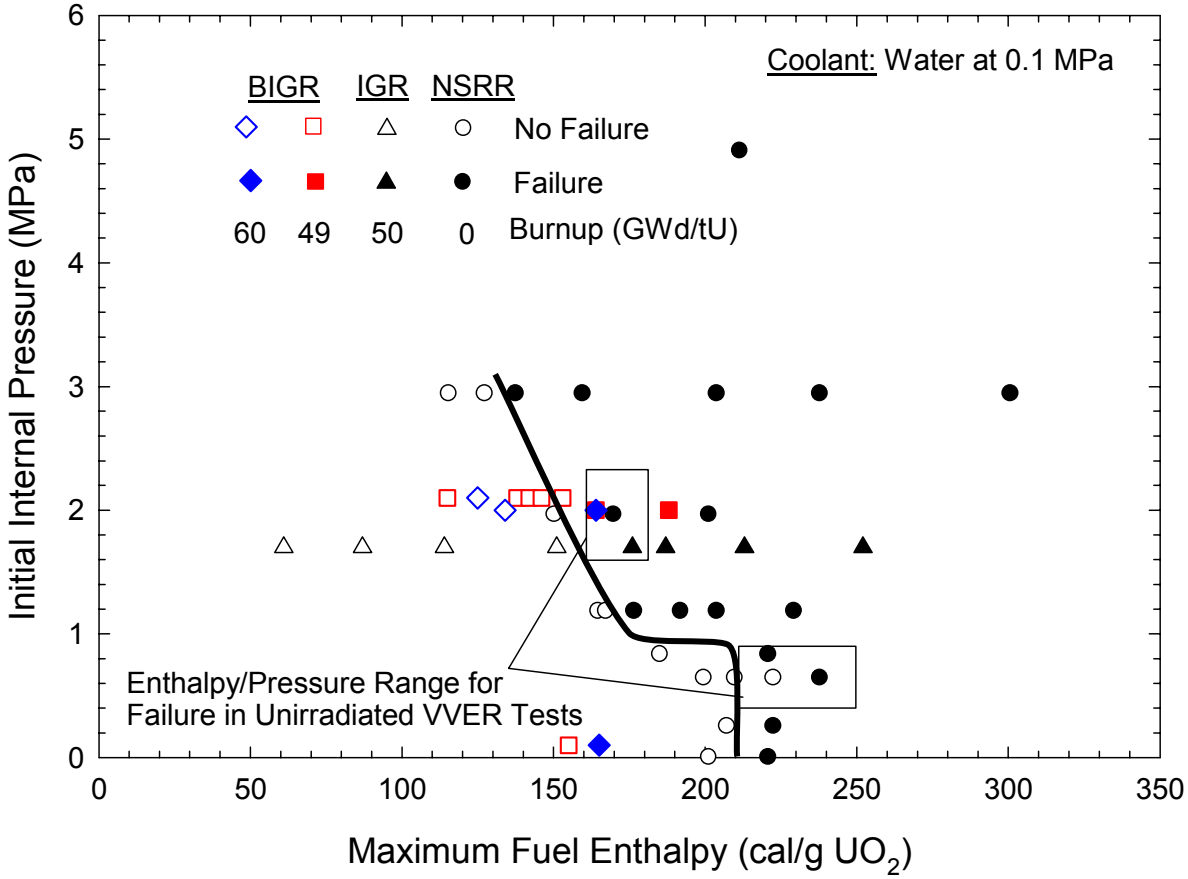
Observations from Experiments on BWR Rods at 20ºC and Narrow Power Pulses

- Two different failure modes clearly distinguished from experiments performed at low temperatures:
  - PCMI failure identified in NSRR and SPERT experiments
  - Ballooning failure identified in NSRR and Russian (IGR and BIGR) experiments with pressurized rods
- PCMI failures observed in the range of 147 cal/g (for zero burnup) to 60 cal/g (for high burnup)
  - PCMI failure related to the loss of ductility due to cladding oxidation/hydriding combined with low temperatures and narrow power pulse shape (< 10 millisecond)
- Ballooning failures observed in the range of 195 cal/g (for zero burnup) to 140 cal/g (for high burnup)
  - Ballooning failure due to cladding heatup at high rod internal pressures

PCMI Failures in High Burnup BWR Fuel



High Temperature Ballooning Failures



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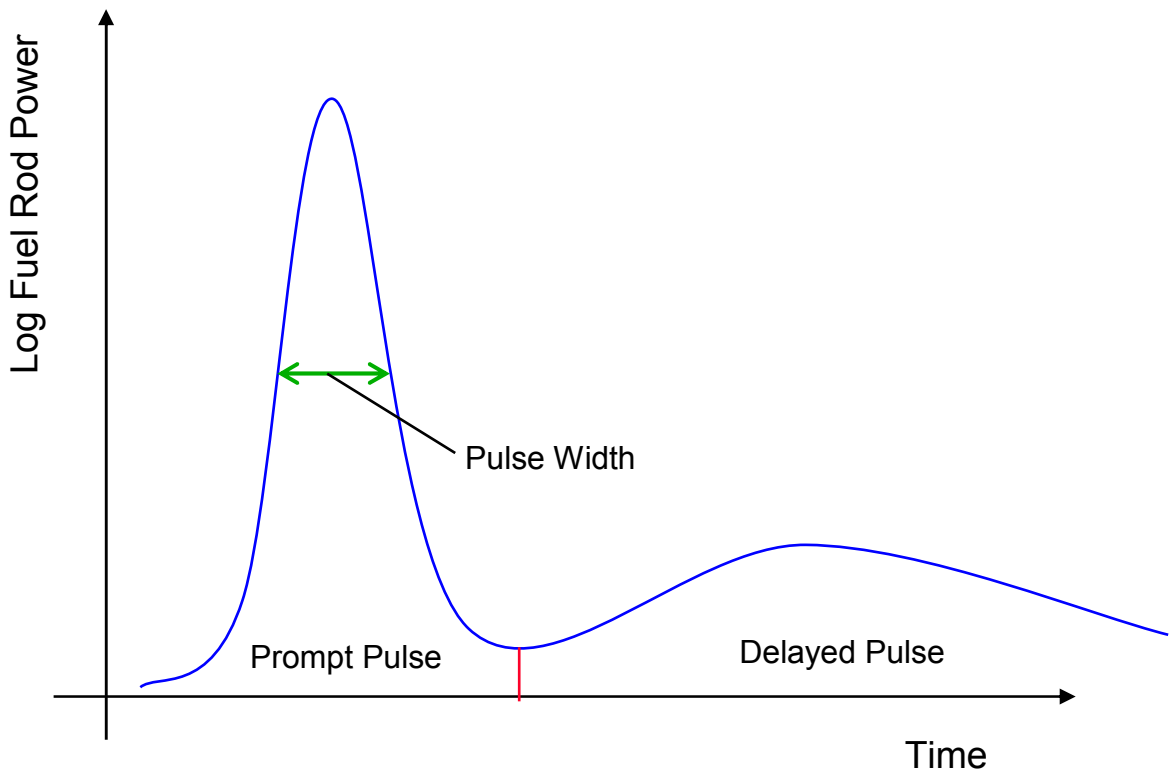
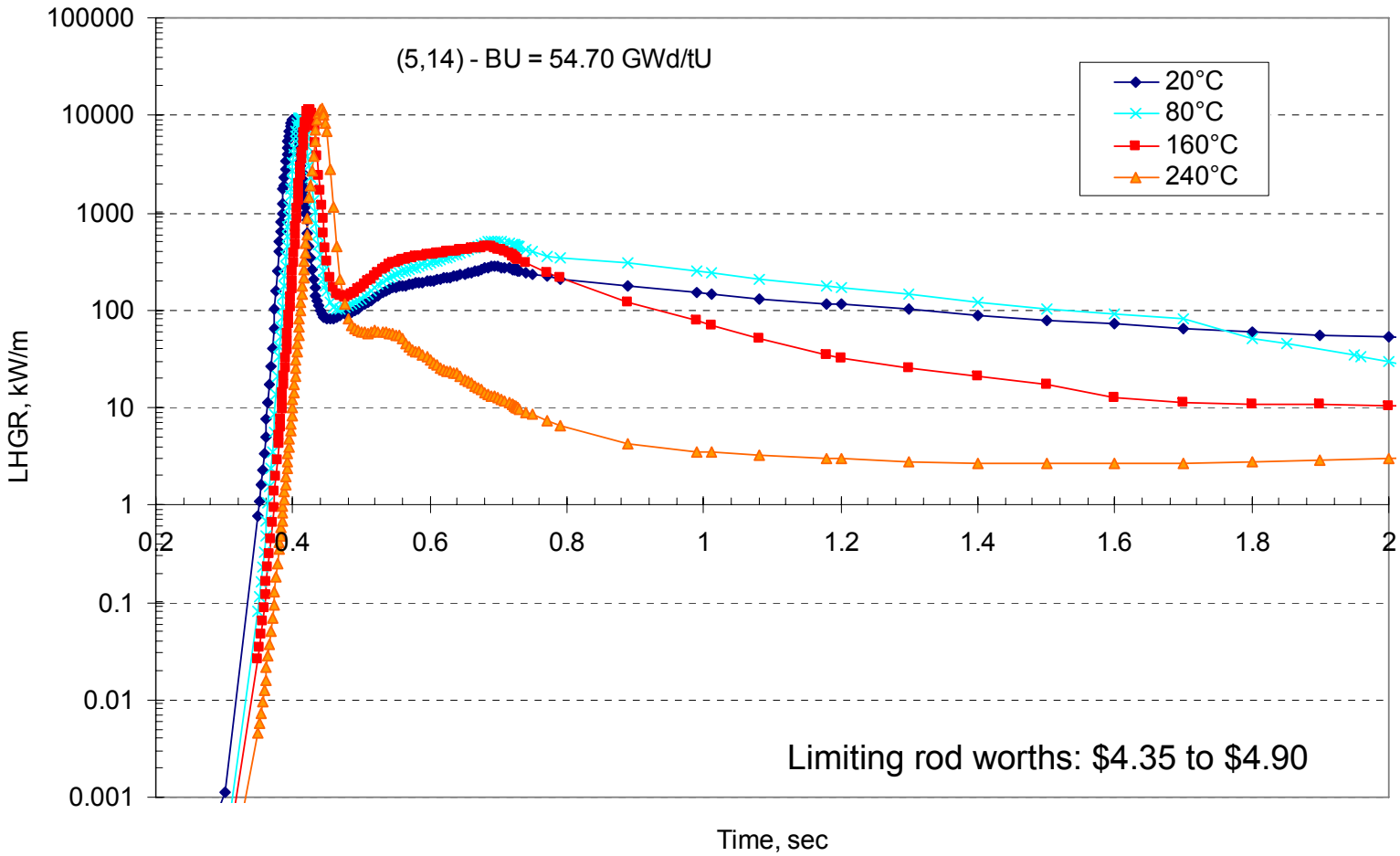
BWR Specific Issues for Interim Failure Threshold Development

- BWR-specific Power Pulse Characteristics
  - Ratio of prompt to total energy deposition is lower for high subcooling conditions
  - Power response impacts fuel rod enthalpy/temperature response
- Mechanical properties of irradiated Zr-2 BWR cladding exhibit strong temperature and hydrogen dependencies
  - Low moderator temperatures will be limiting condition
- BWR Cladding Oxide and Hydrogen Accumulation
  - Must consider the hydrogen\oxide relationship differences
- Multiple Cladding Failure Modes
  - PCMI during prompt energy deposition
  - Ballooning and burst during delayed energy deposition

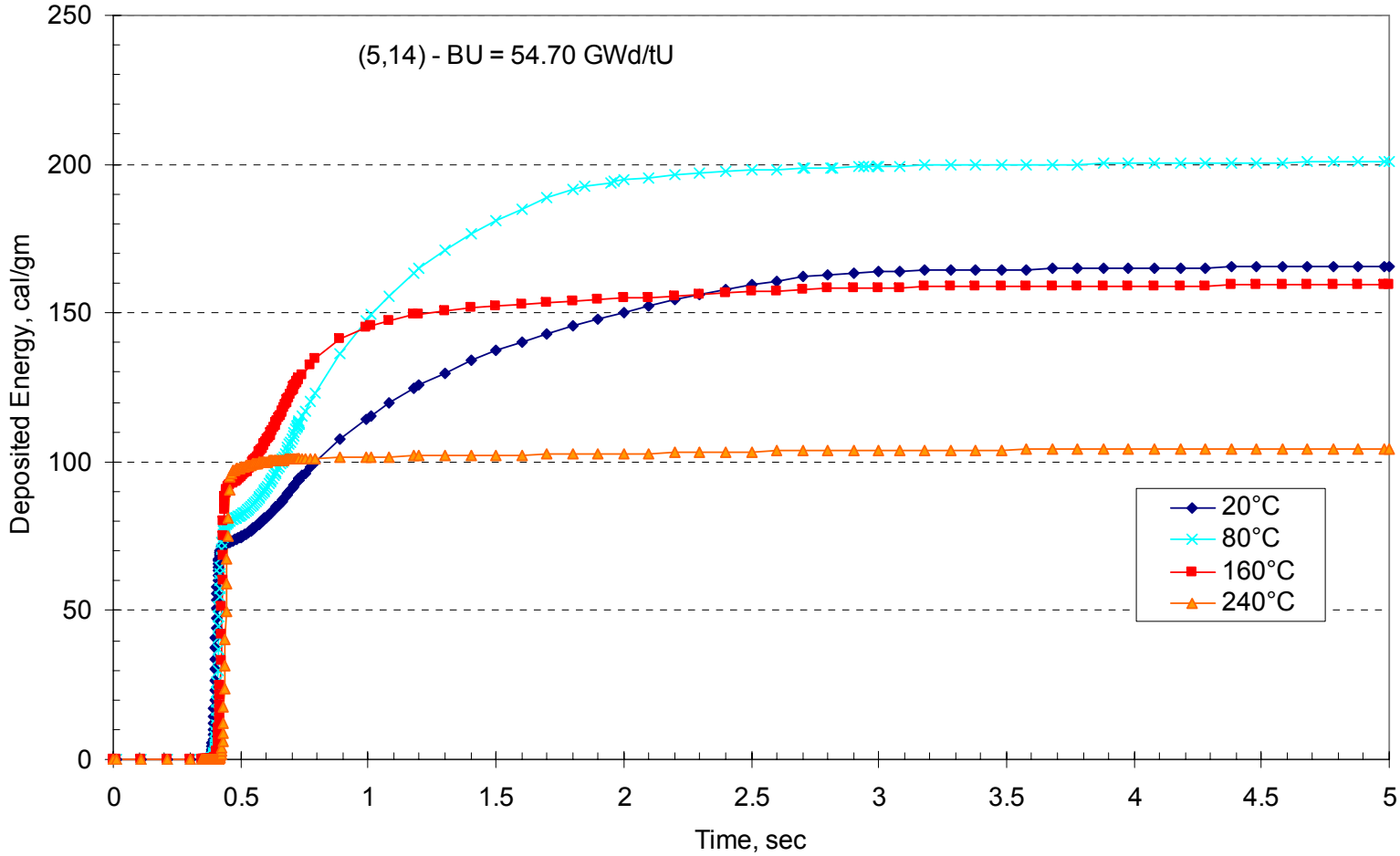
Schematic of BWR CRDA Power Pulse



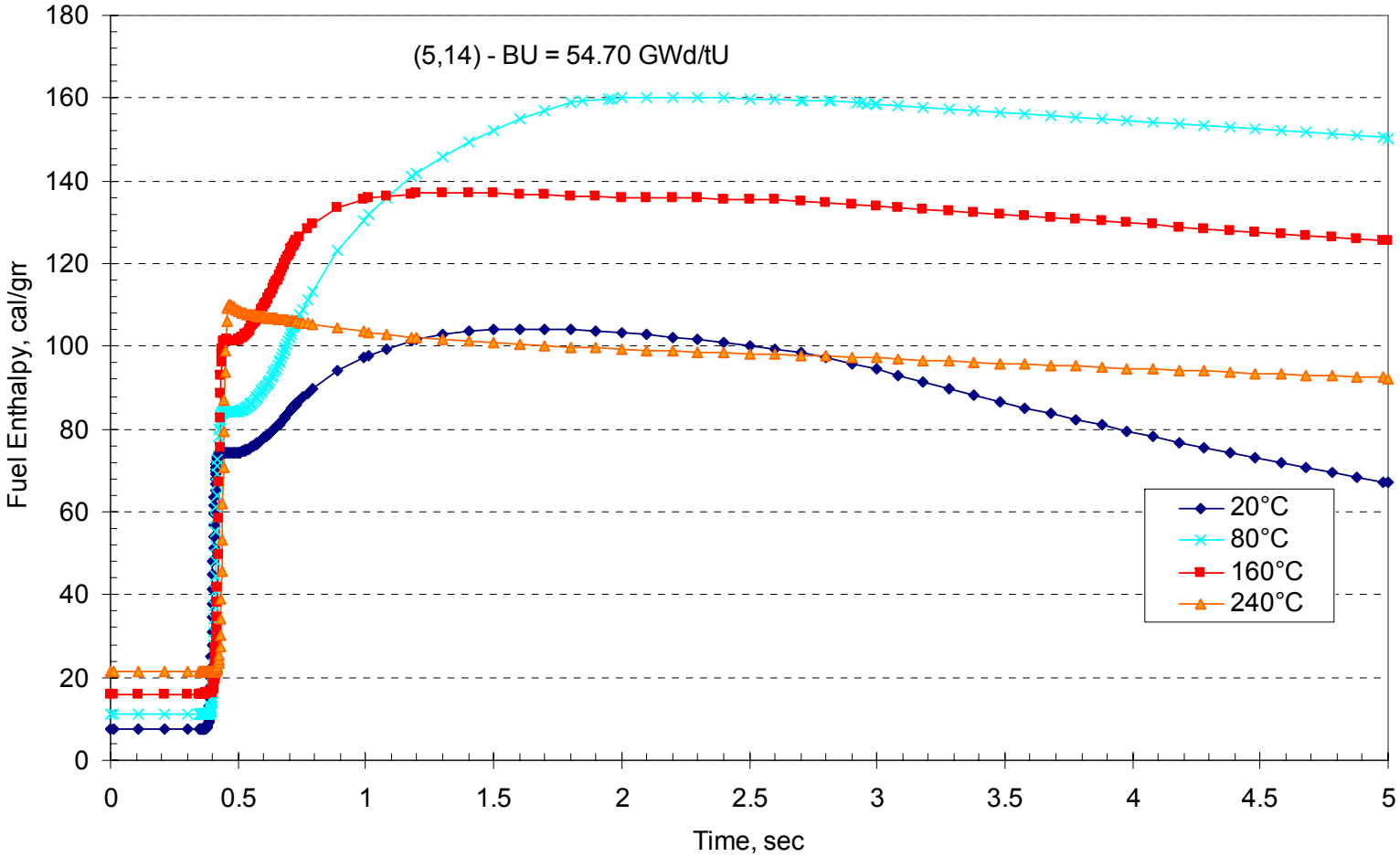
Moderator Temperature Effect on Pulse Response



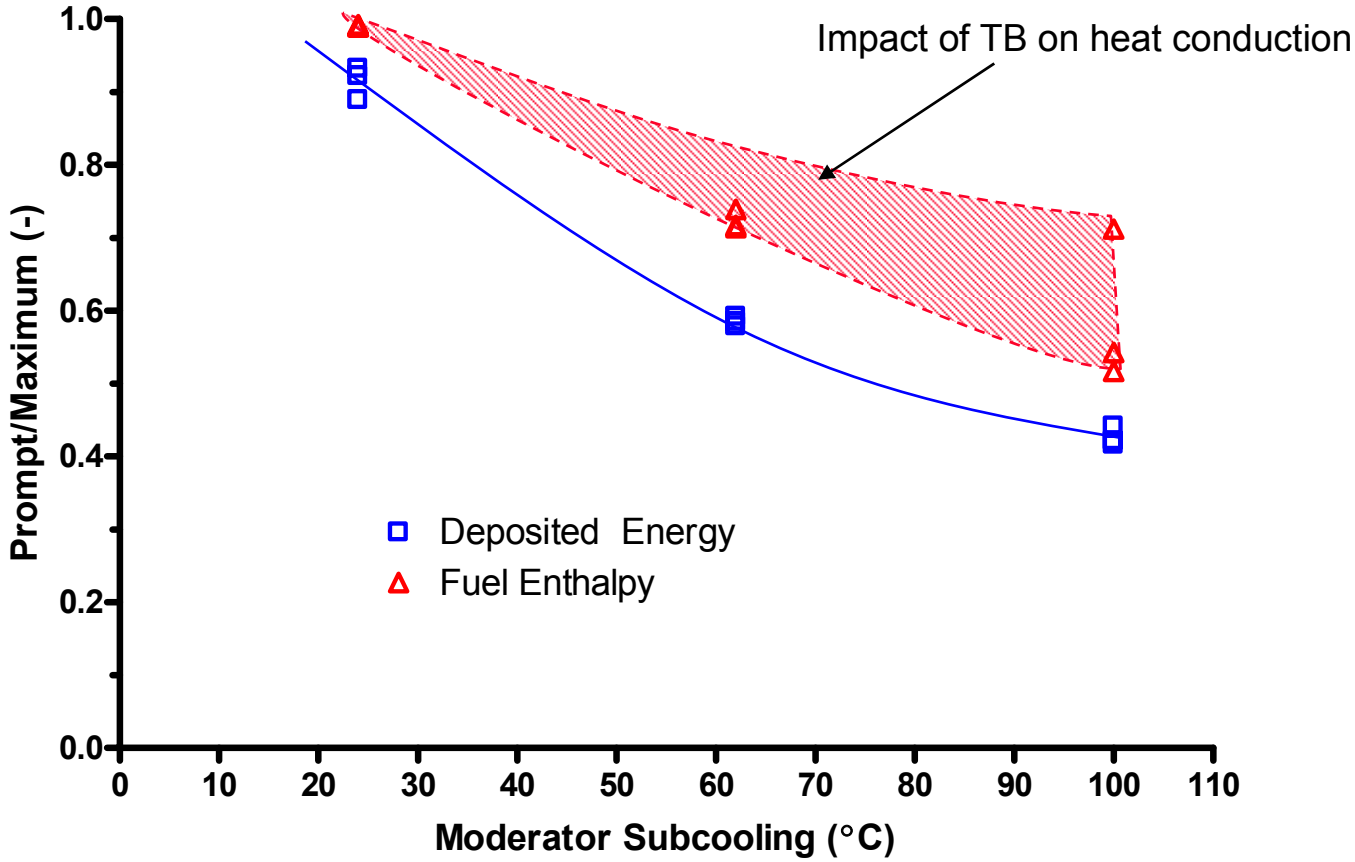
Moderator Temperature Effect on Deposited Energy



Moderator Temperature Effect on Fuel Enthalpy

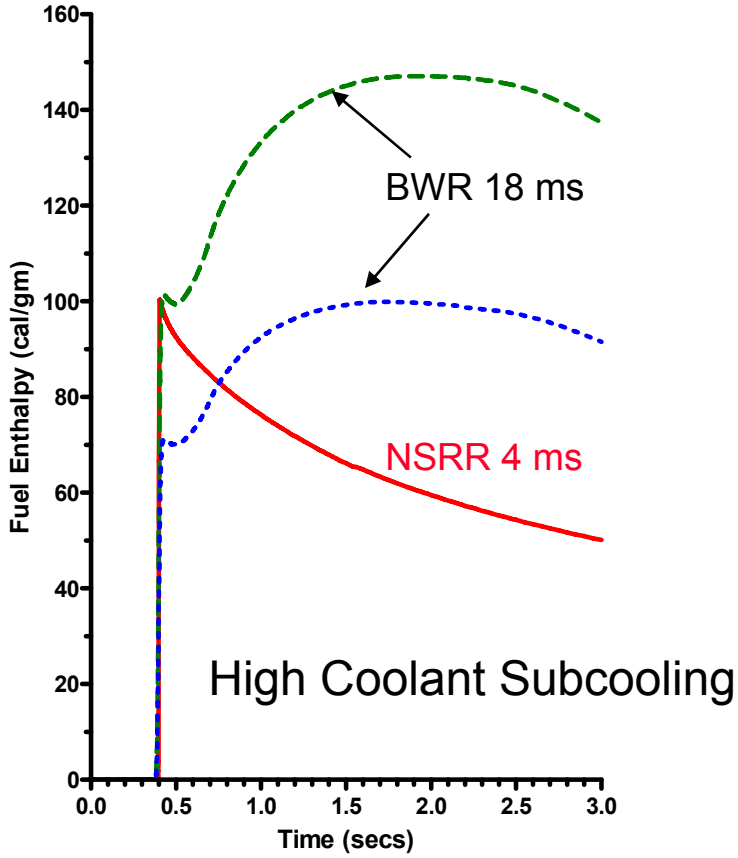


Prompt and Maximum Energy/Enthalpy

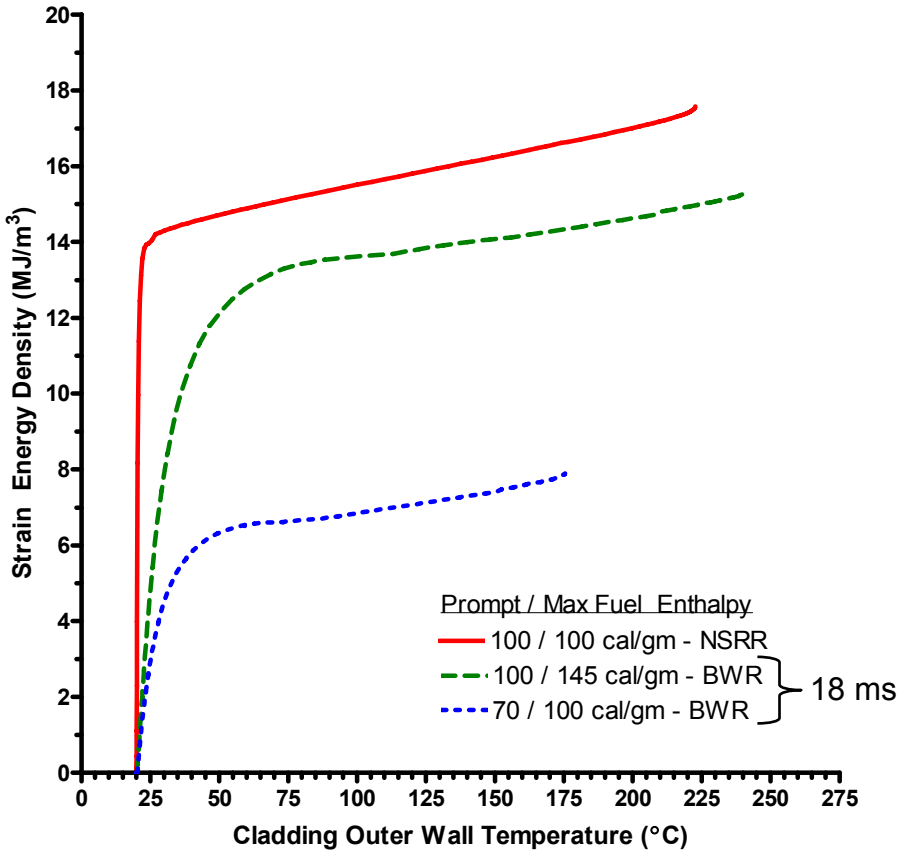


Fuel Rod Behavior
NSRR vs. BWR CRDA

Fuel Enthalpy Response

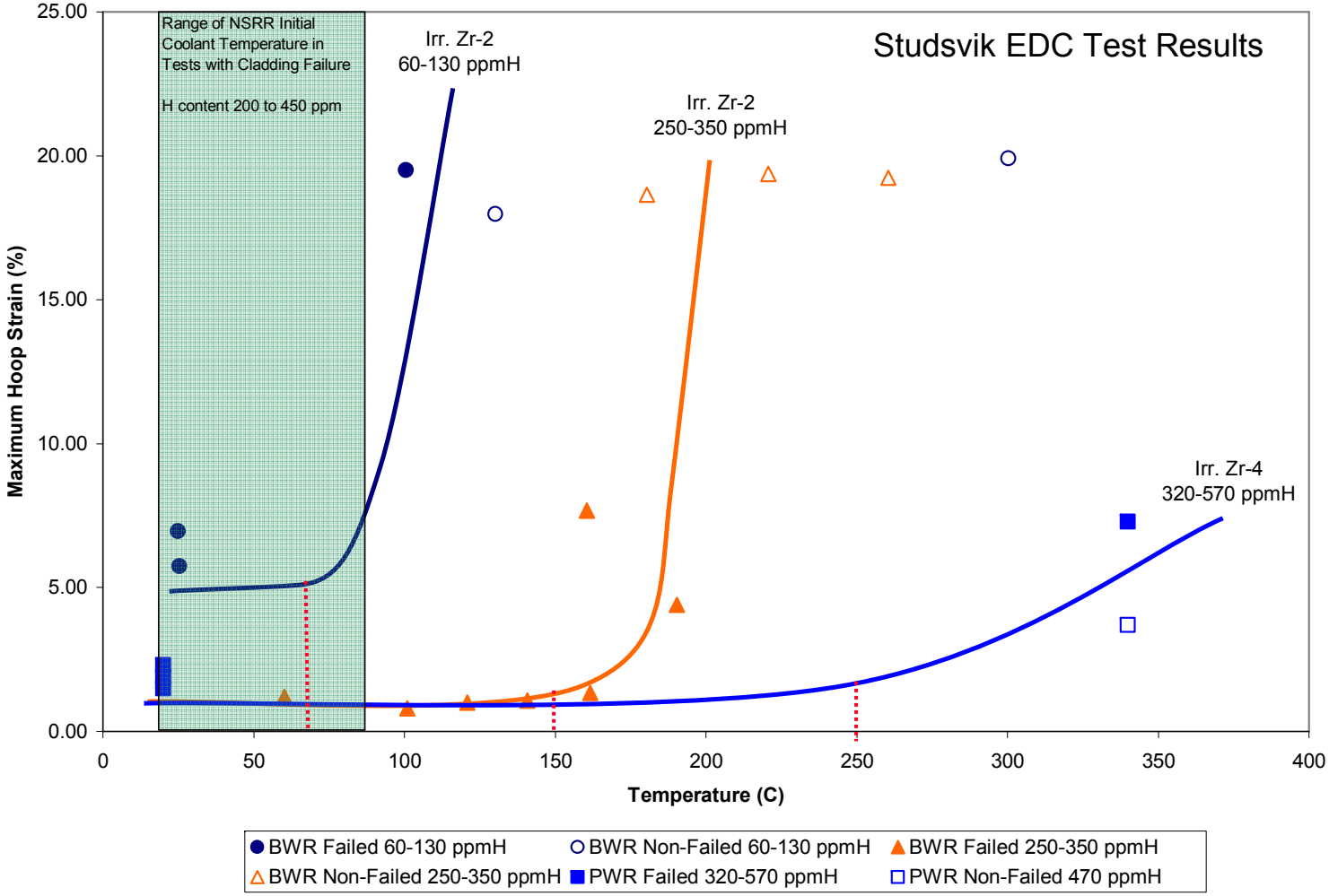


Cladding Thermal/Mechanical Response

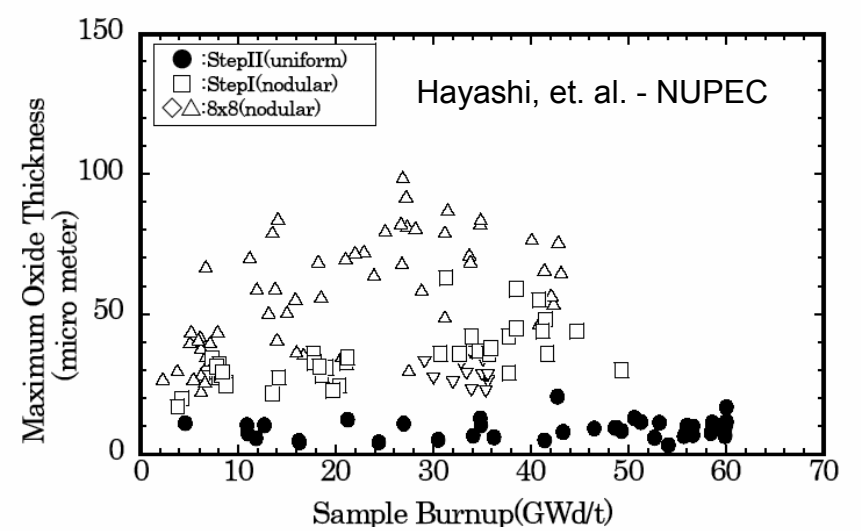


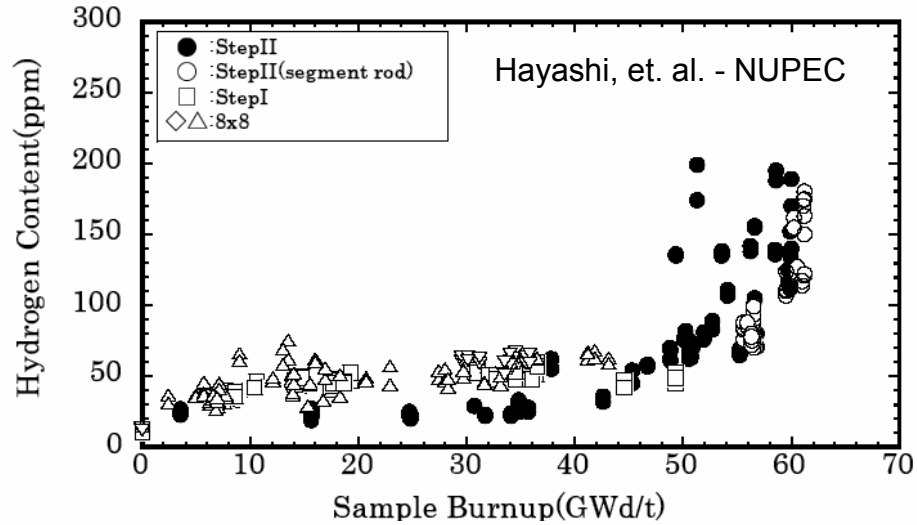
NSRR conditions are conservative and apply only to prompt energy deposition

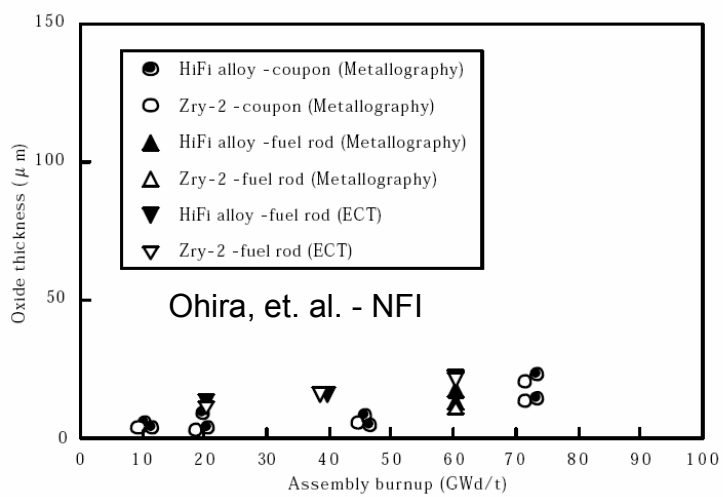
Temperature and Hydrogen Effects on BWR Cladding Mechanical Behavior

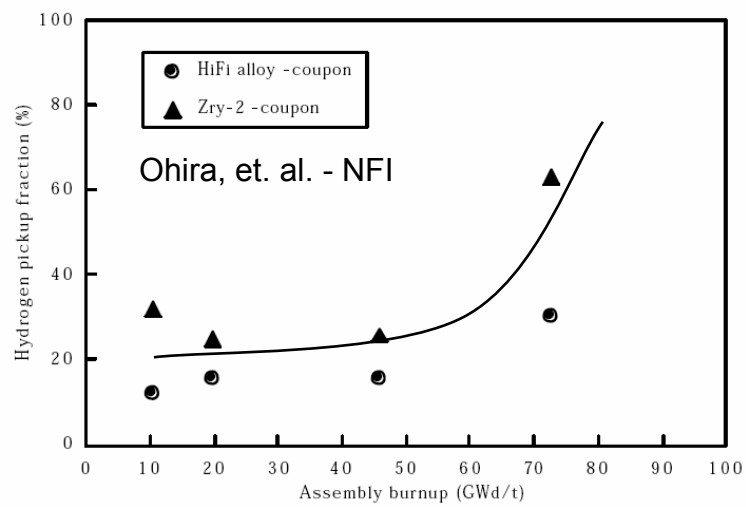


Zr-2 Cladding Corrosion and H-Pickup

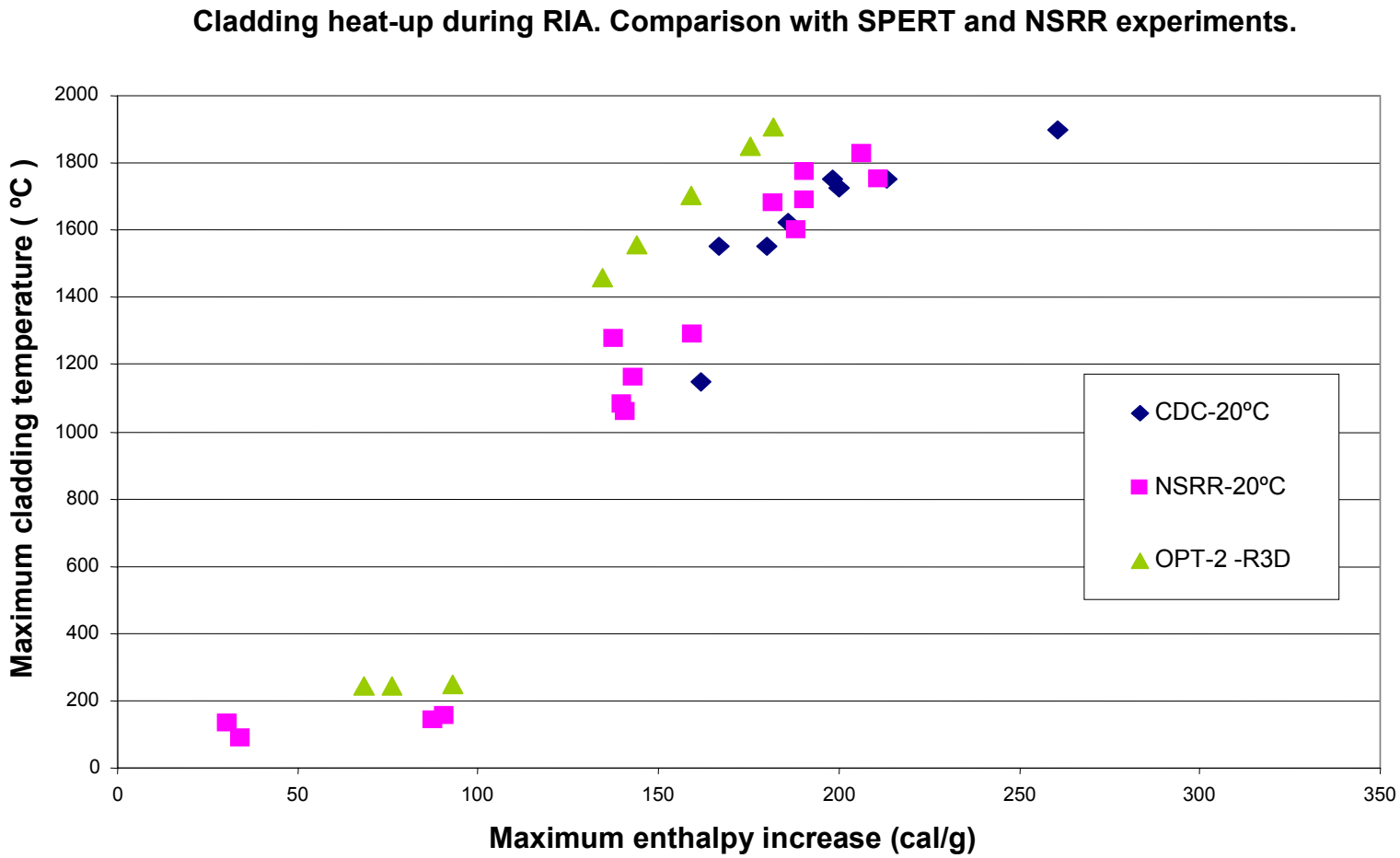








Effect of Post-TB Heat Transfer on Cladding Temperature



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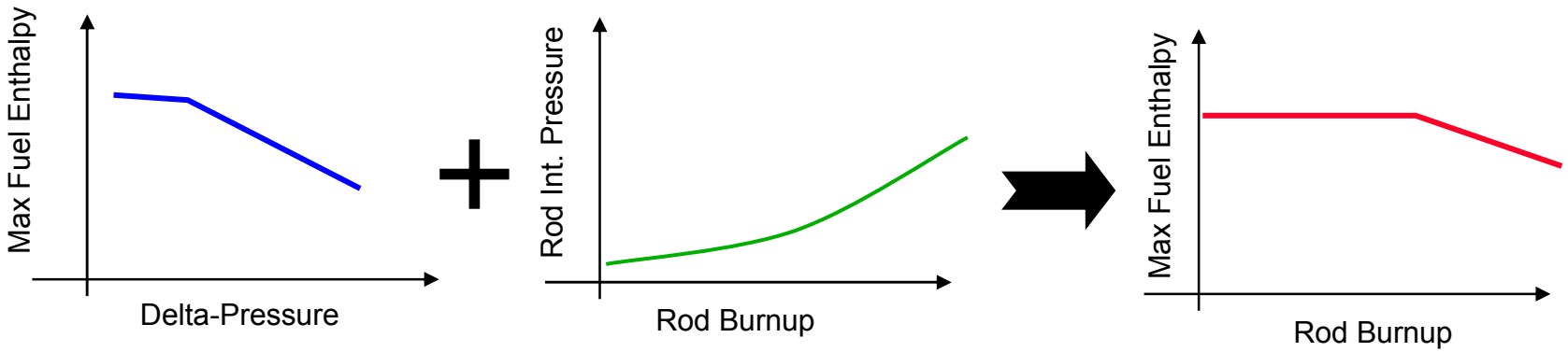
Approach to Interim BWR Failure Threshold

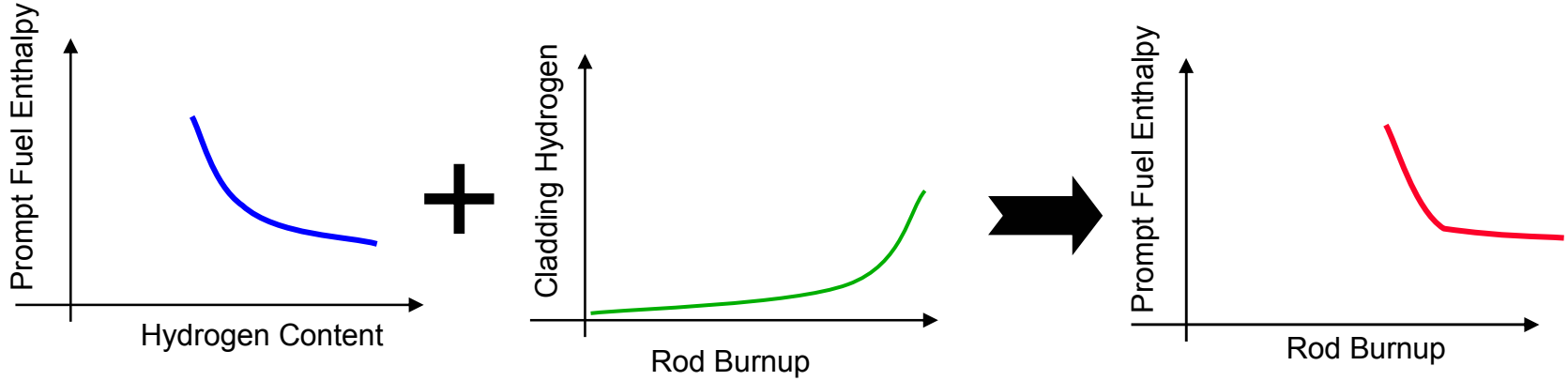
- PCMI failure possible at BWR CZP conditions only during the initial enthalpy rise (low cladding temperatures)
  - Prompt enthalpy is the appropriate variable to determine if the PCMI failure limit is exceeded (@ time of max power plus 1 pulse width)
  - Prompt enthalpy at failure function of hydrogen content (and possible relation to exposure)
  - NSRR data needs to be adjusted for pulse width effects
- Ballooning failure possible at BWR CZP conditions during the delayed enthalpy rise (high cladding temperatures)
  - Total enthalpy is the appropriate variable to determine if the ballooning failure limit is exceeded
  - Total enthalpy at failure function of delta-pressure (or burnup)
- Two different limits could be used for the interim rod failure threshold for BWR CRDA at CZP conditions
  - Similar approach already used by the Japanese regulators

Approach to Develop BWR Failure Threshold

Maximum Fuel Enthalpy Threshold for Ballooning Failure

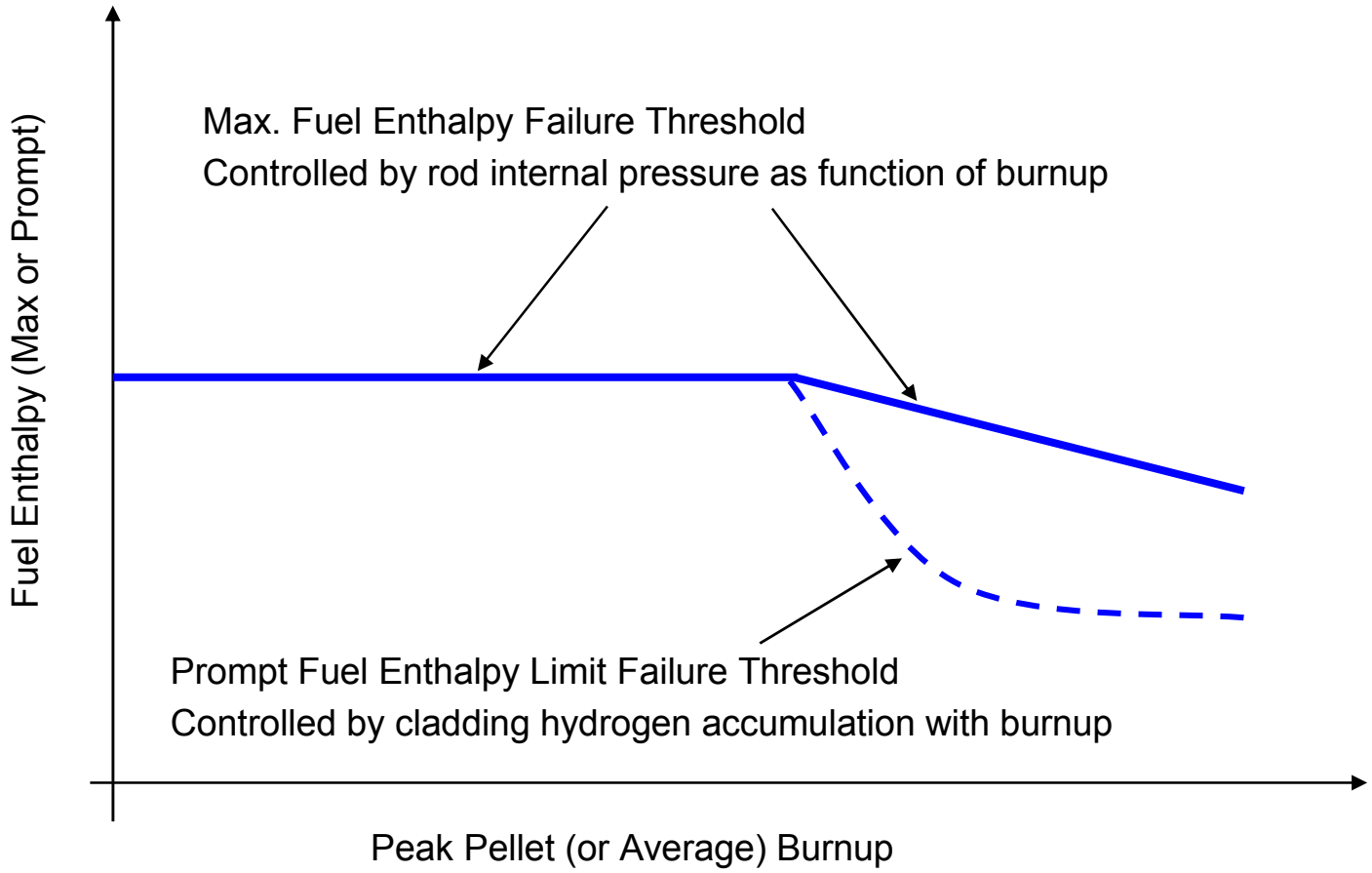


Prompt Fuel Enthalpy Threshold for PCMI Failure



Conceptual Format of BWR Failure Threshold

Consistent with the GNF Approach



PWR Failure Threshold – Statistical Approach

Alternative Failure Threshold Development

- Alternative methods to address uncertainties in cladding ductility
  - Use statistical lower bound (e.g. 95%) cladding failure model for criteria development, or
  - Develop lower bound CSED model based on reassessment of database (EdF approach-Kyoto Meeting)
- Requires reassessment of other conservatisms
  - Use statistical evaluation of oxide thickness, hydrogen pickup fraction, and mechanical properties
- Continues to keep science in the approach
  - Still retains sound technical and scientific basis
  - Not as overly restrictive as empirical approach using the results from widely different tests

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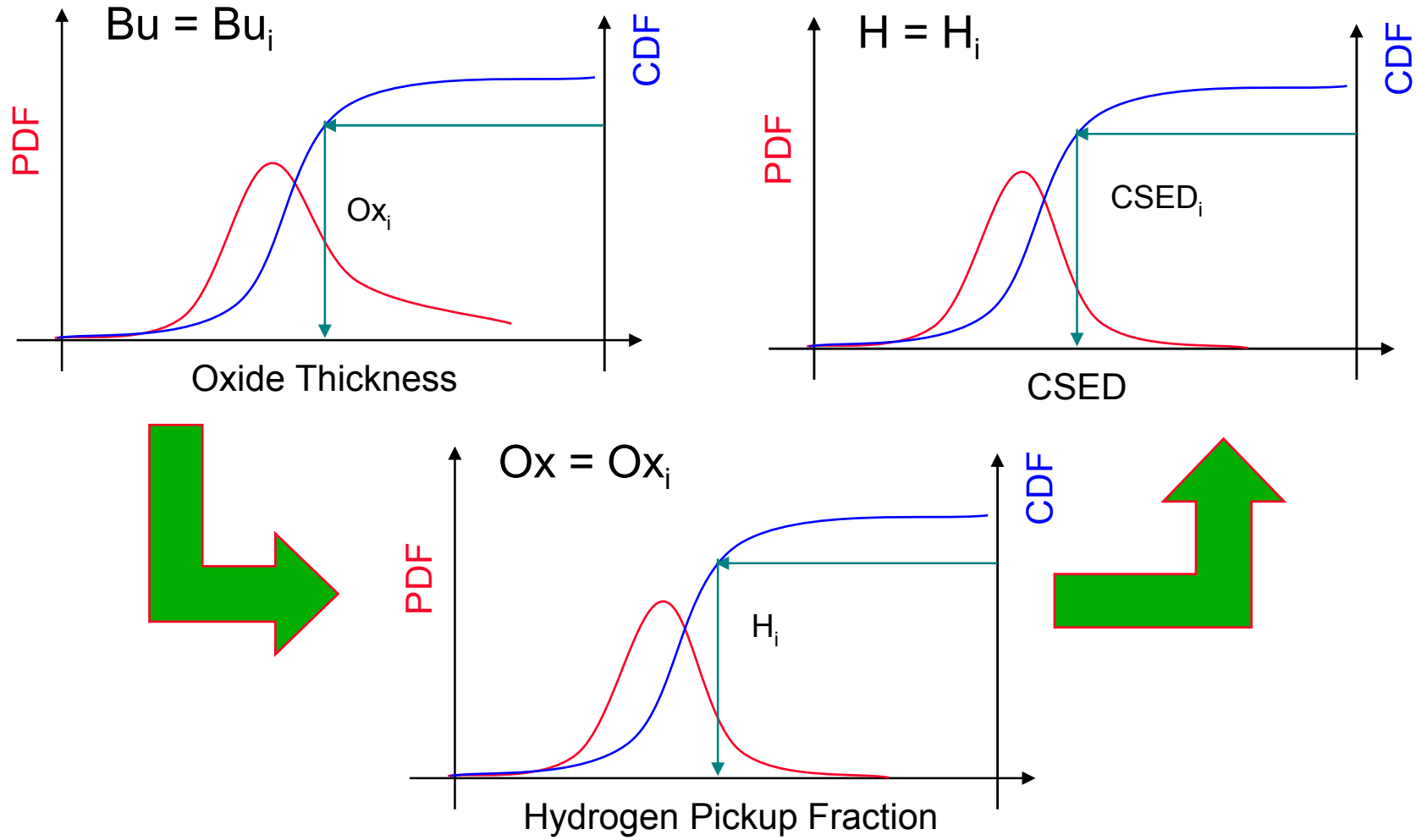
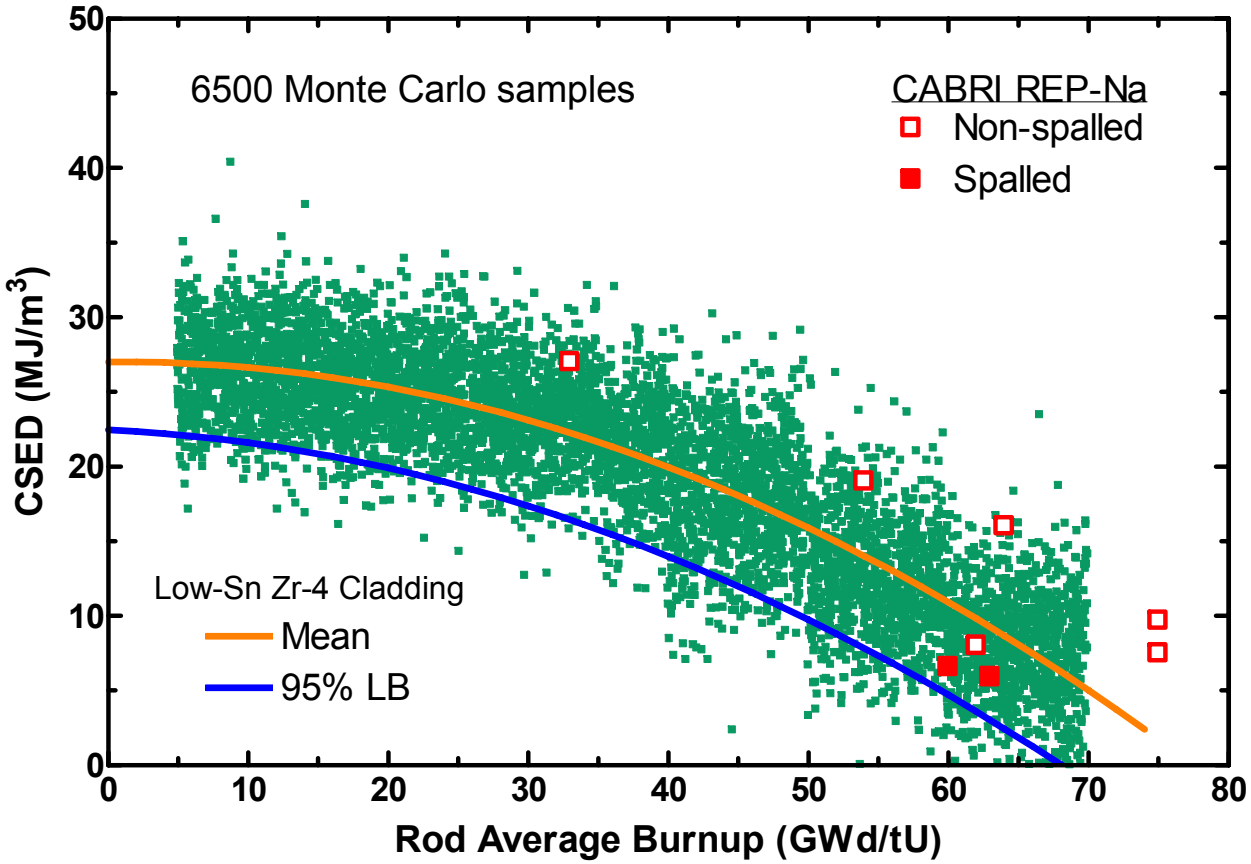
Statistical Approach to Develop Failure Threshold

- Use statistical approach to include impact of uncertainties on cladding mechanical response during RIA
  - Account for uncertainties in oxide thickness accumulation, hydrogen content, and mechanical properties (burst tests)
- Evaluate the uncertainties using standard statistical methods
  - Develop Gaussian or log-normal probability distribution functions (PDFs) for key variables (oxide thickness, hydrogen pickup, and mechanical properties)
- Use Monte Carlo technique to combine uncertainties
  - Results in scatter plot of CSED versus burnup
  - Develop lower 95% cladding failure model (CSED)
- Use lower 95% cladding failure model to construct failure threshold using analytical method
  - Provides fuel enthalpy at failure versus burnup

Schematic of Approach to Address Uncertainties in Cladding Performance

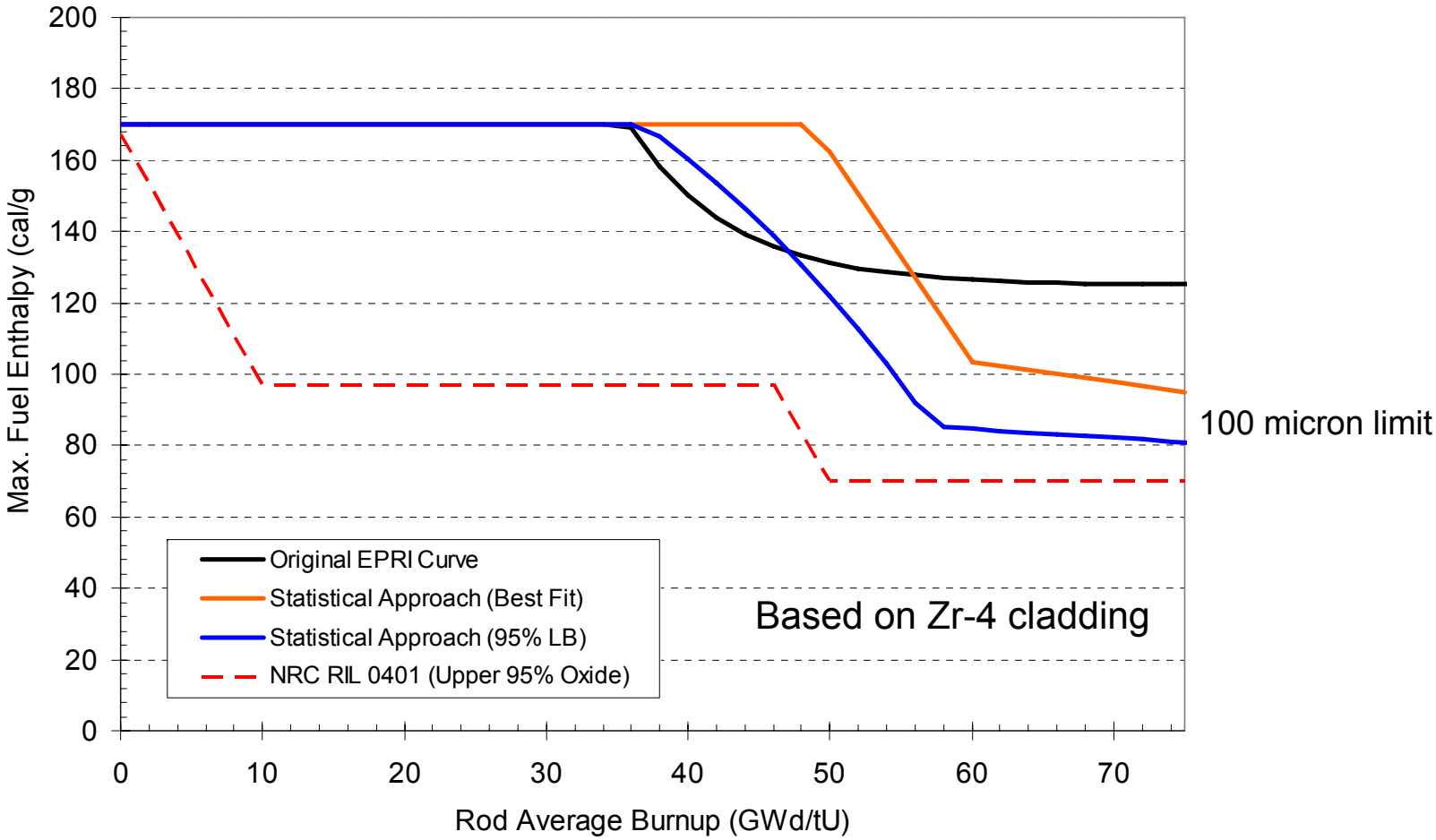


Statistical Distribution of Zr-4 CSED vs Rod Average Burnup



Developed without limits on maximum oxide thickness or hydrogen content (includes spallation)

RIL-0401 Limit is Below 95/95



Additional Conservatisms in Approach

- Burst tests over-estimate cladding failure potential for PCMI conditions
  - Failure strains higher for displacement loading conditions
- Effects of spalled rods included in cladding mechanical properties
  - Low probability of spallation in modern cladding types improves cladding mechanical performance
- Corrosion data from older cladding materials has higher uncertainties compared to newer cladding types
  - Less variability in mechanical performance of modern cladding types

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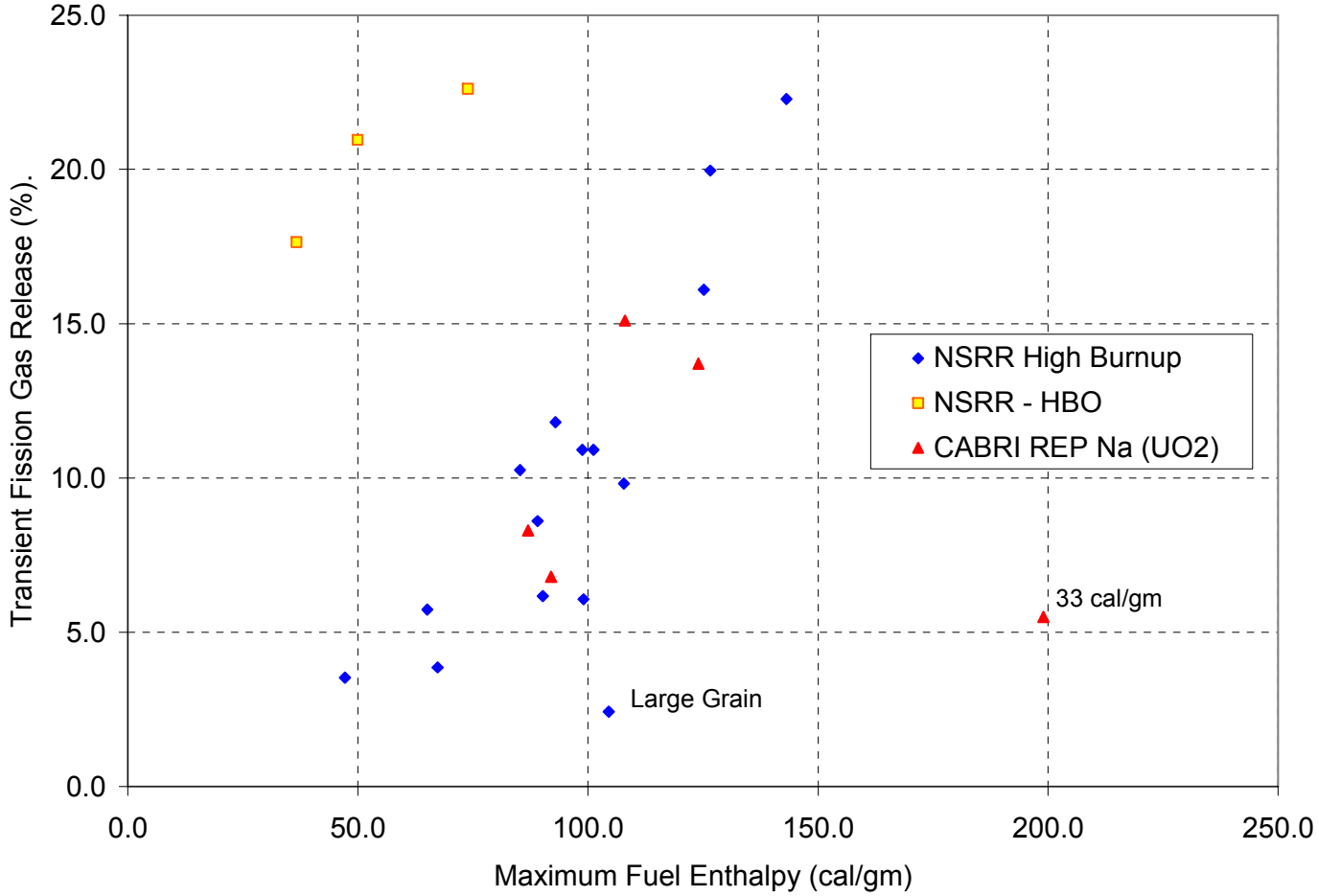
Interim Failure Threshold Development

- Industry is willing to consider other approaches
  - Alternative approaches to account for uncertainties in cladding failure behavior have been considered
- Mechanistic approach combined with statistical treatment of uncertainties can be used
  - Allows for the conservative treatment of material variability with irradiation
  - Maintains sound technical basis
  - Results in less restrictive failure threshold compared to RIL 0401
- A low interim failure threshold at high burnup can be accommodated provided
  - Separation between coolability limit and failure threshold is maintained

RIA Transient Fission Gas Release

Transient FGR function of fuel enthalpy and grain boundary gas concentration (burnup)



Transient FGR Source Term

- Transient FGR is limited to small region of the core
  - Radial and axial power distribution leads to less than 5% of core having transient fission gas release

$$\mathrm{Gap}_{inv} = \underbrace{\overbrace{\int_{z_{bot}}^{z_{top}} \mathrm{FGR}_{ss} \cdot \mathrm{FP}_{inv}(z)\,dz}^{\text{Steady State FG Gap Inventory}}}_{\text{Rod Average = 2\% to 10\%}} + \underbrace{\overbrace{\int_{z_{bot}}^{z_{top}} \mathrm{FGR}_{tr}(H(z)) \cdot \mathrm{FP}_{inv}(z)\,dz}^{\text{Transient FG Gap Inventory}}}_{\text{Rod Average = 1\% to 4\%}}$$

- Improved methods results in fission gas release source term that is lower than from older methods
  - Using 10% fission gas release for the gap inventory for all failures is most likely bounding

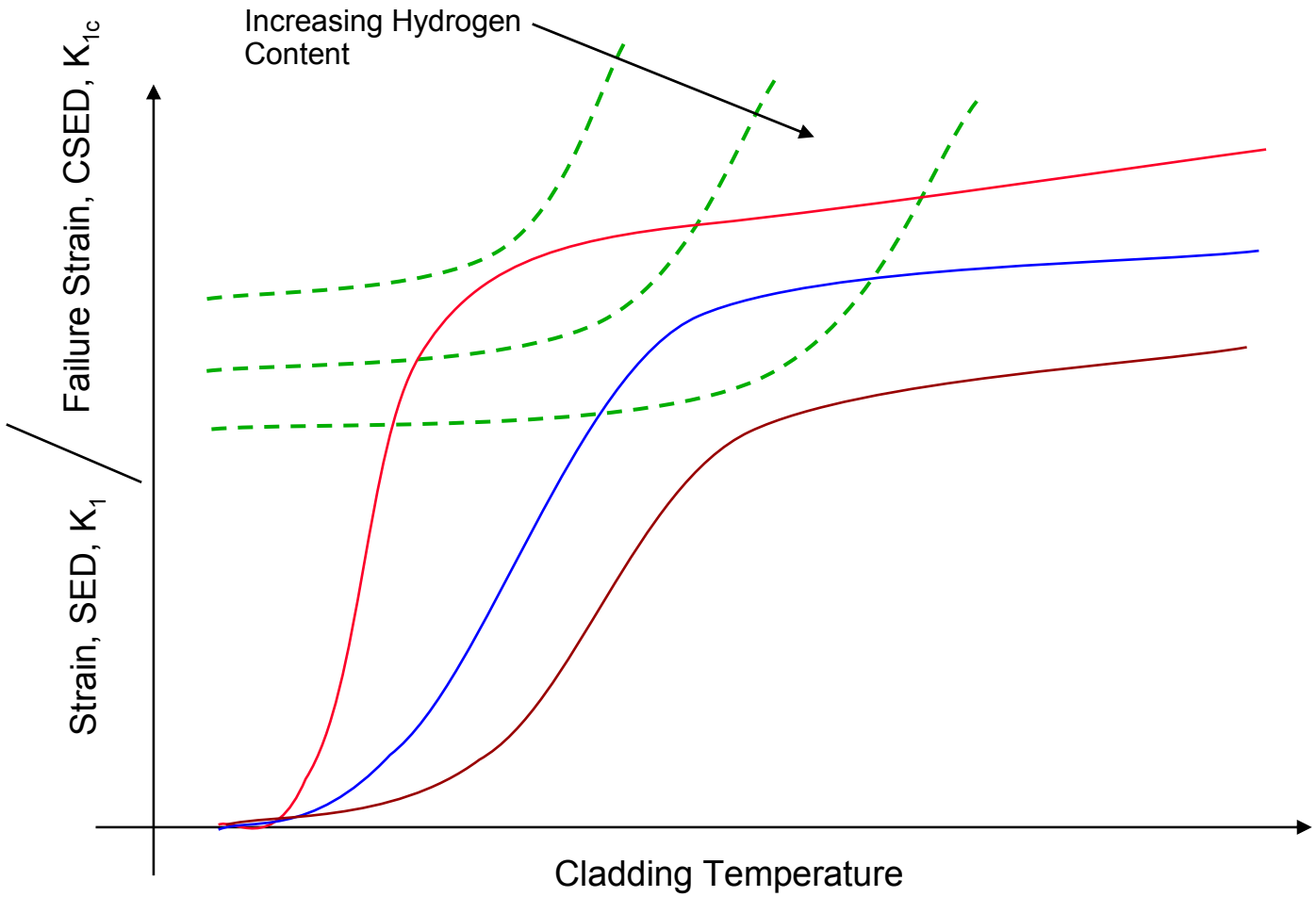
Backup Slides

NRC Position on Core Coolability

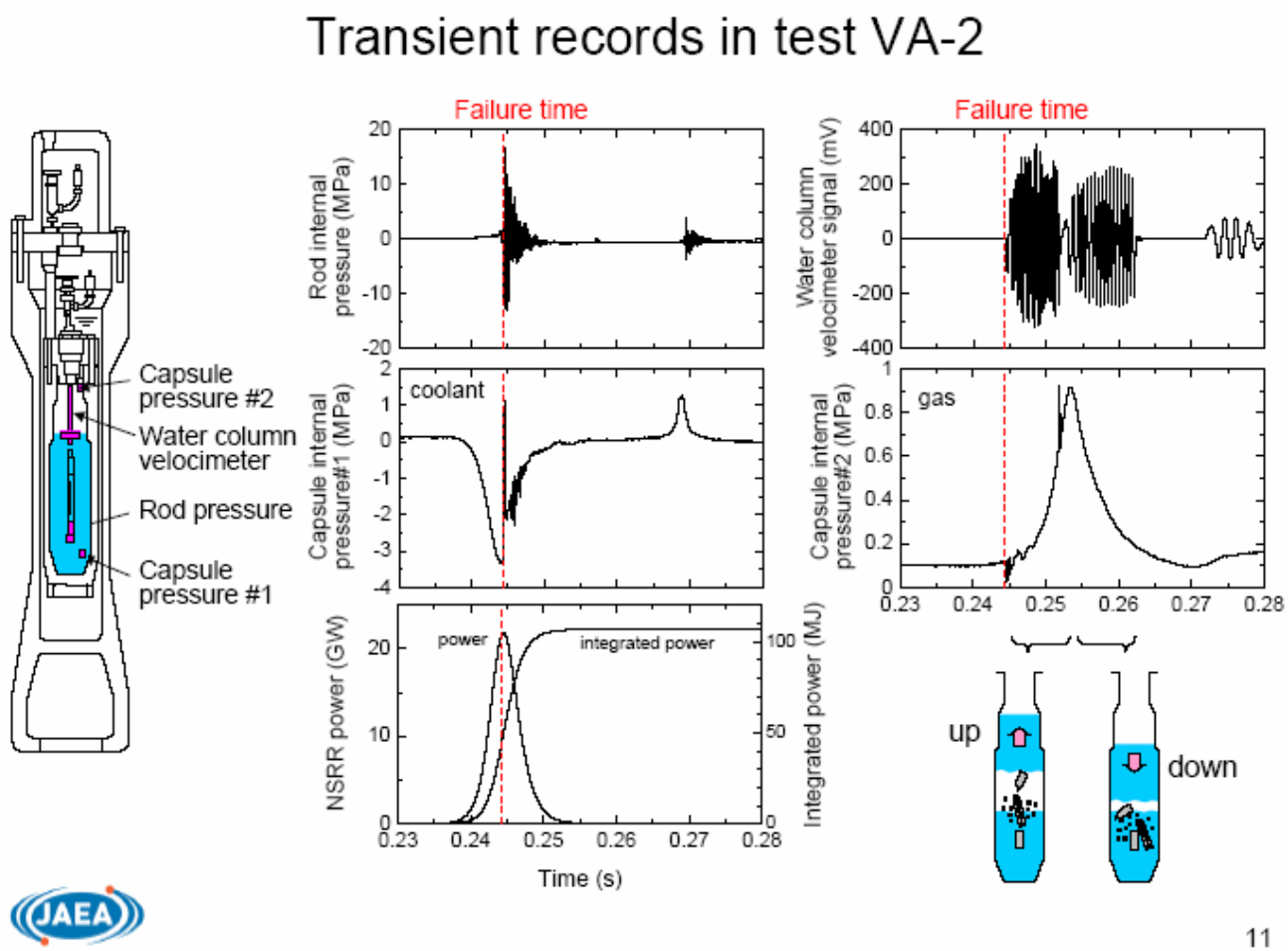
- NRR Concern from SER on RIA Topical Report:
  - Insufficient data and analysis to translate NSRR fuel dispersal data/consequences to LWR pressure pulses (RAI C-3)

- NRC-RES Recommendation (RIL 0401)
  - GDC 28 requires limit on reactivity insertion to prevent damage to the reactor coolant boundary and to ensure a coolable core geometry
  - Coolability limit at failure threshold meets requirements of GDC 28
  - Preventing fuel failure ensures
    - » No fuel dispersal
    - » No damaging pressure pulses
    - » No loss of coolable geometry

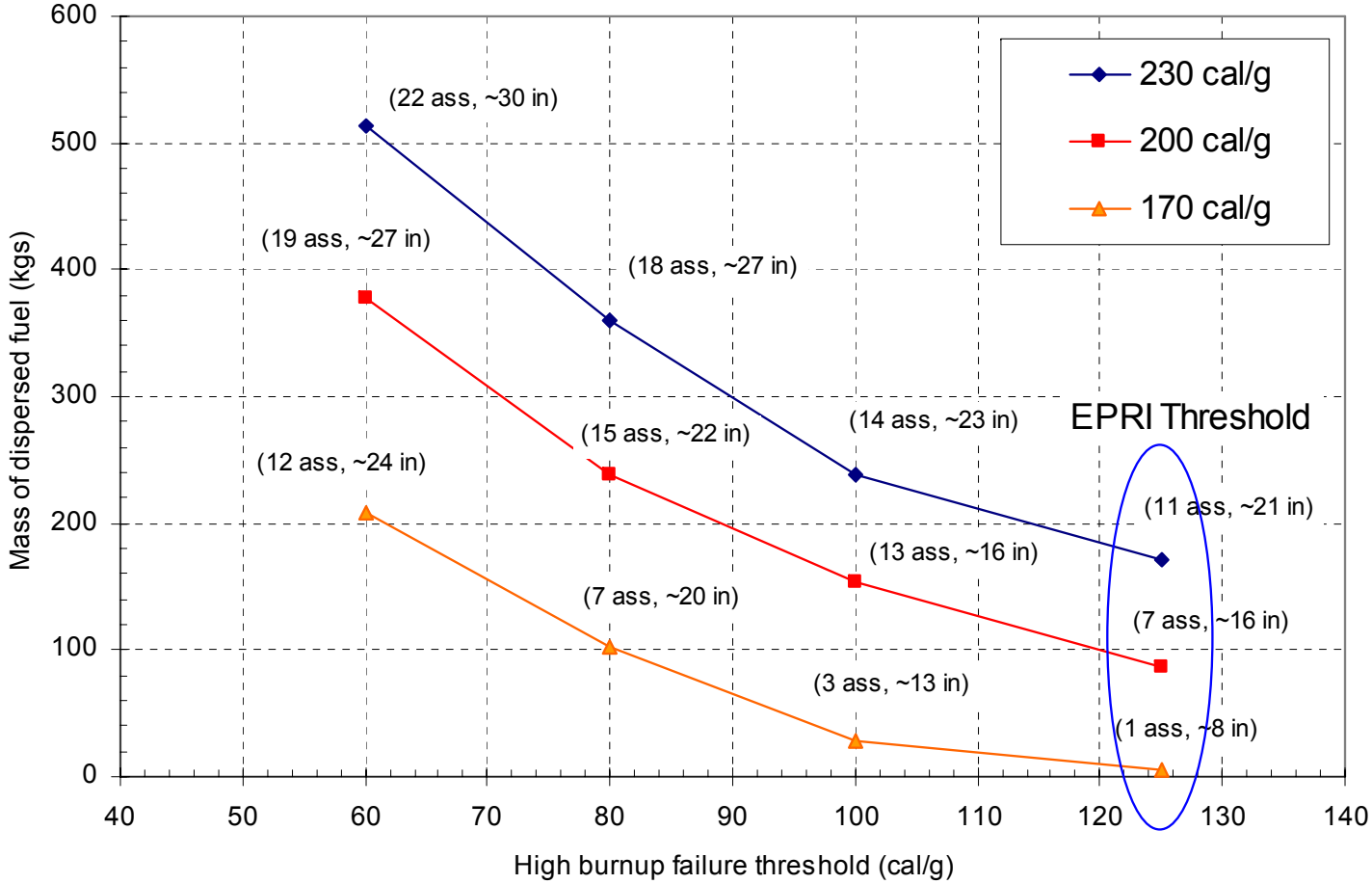
BWR Cladding Failure Behavior



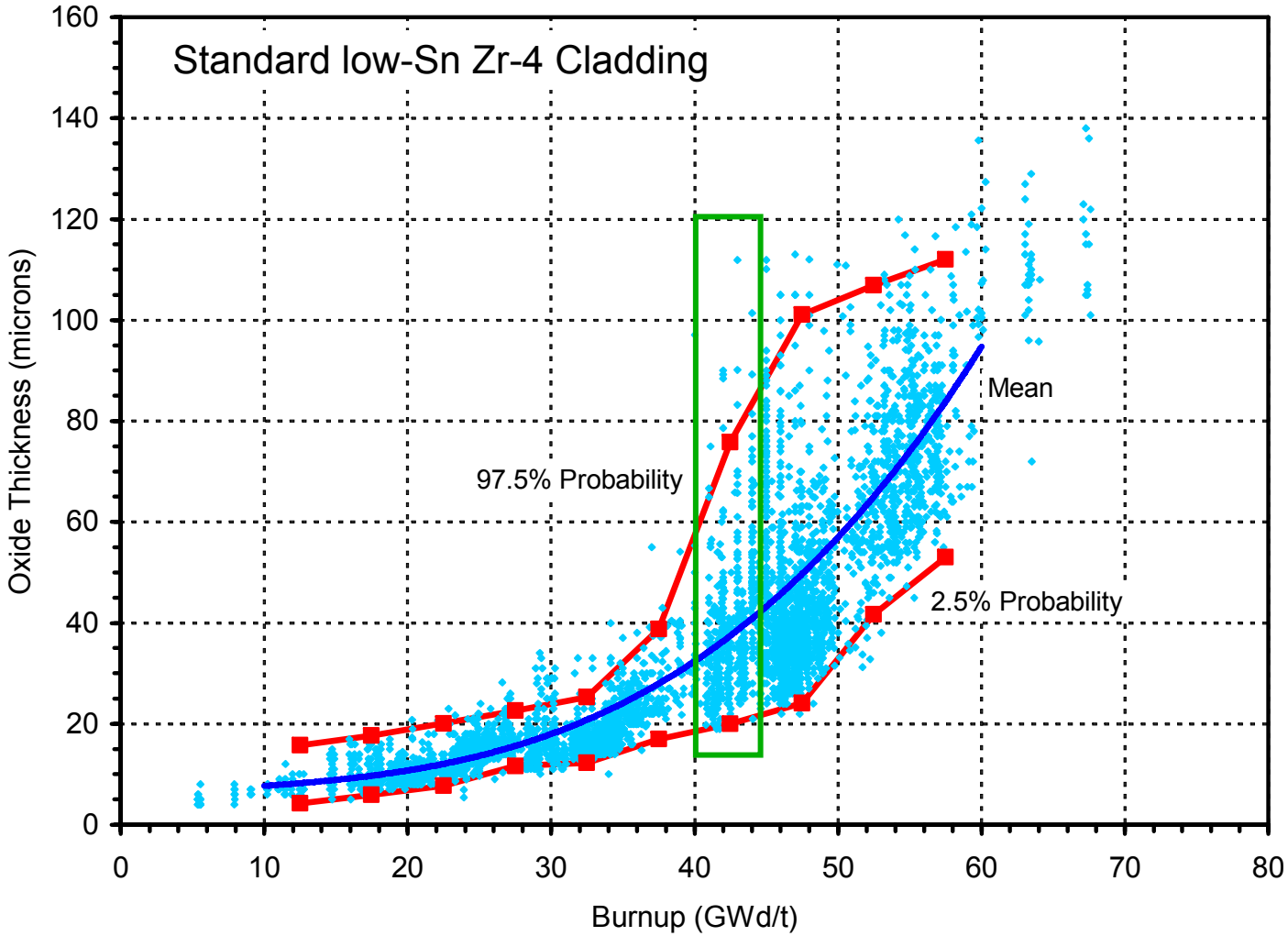
Pressure Pulse Generation after Fuel Dispersal



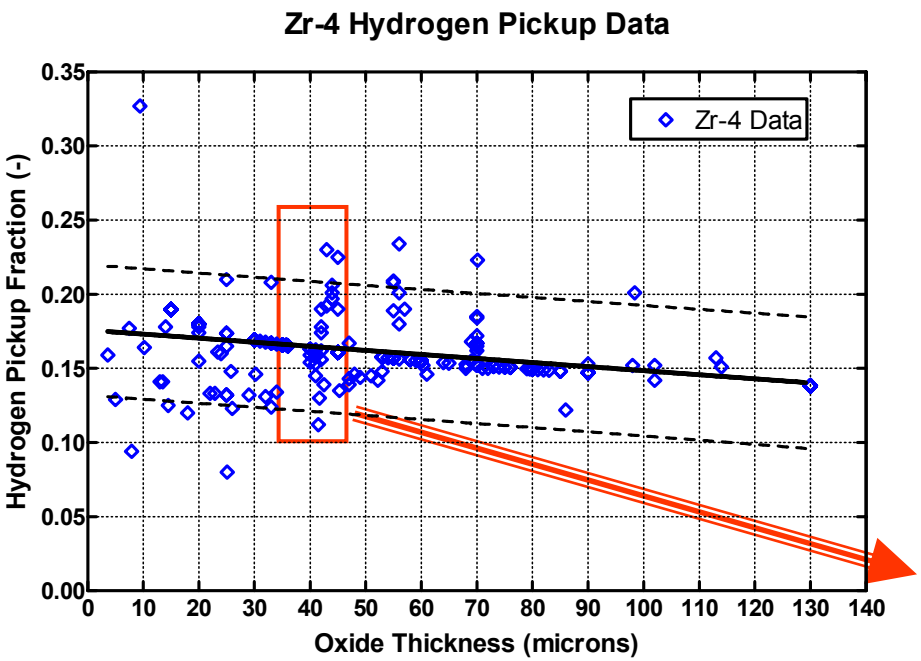
Fuel Dispersal Estimates – PWR



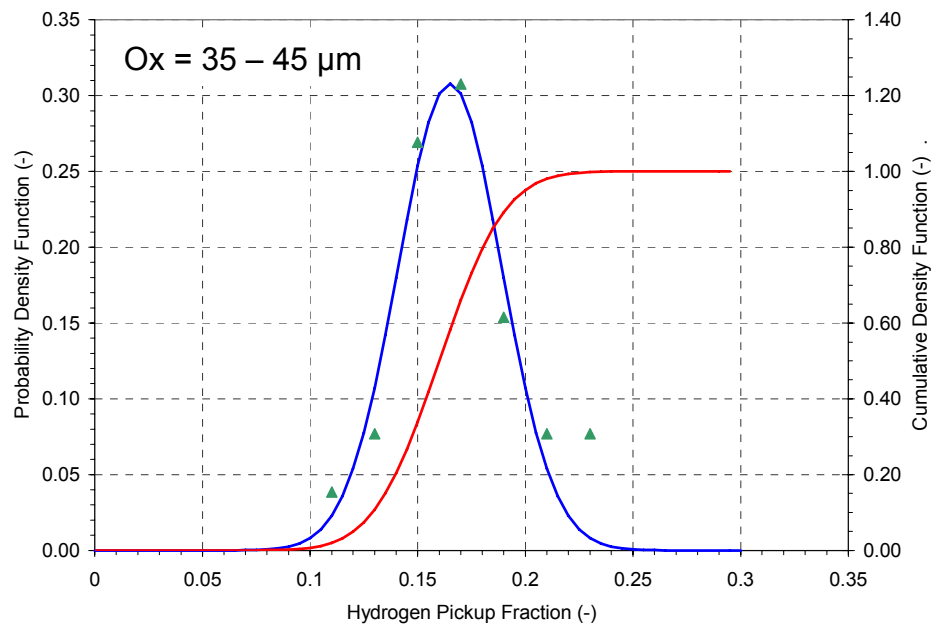
Lognormal Piecewise Evaluation of Oxide Thickness Data



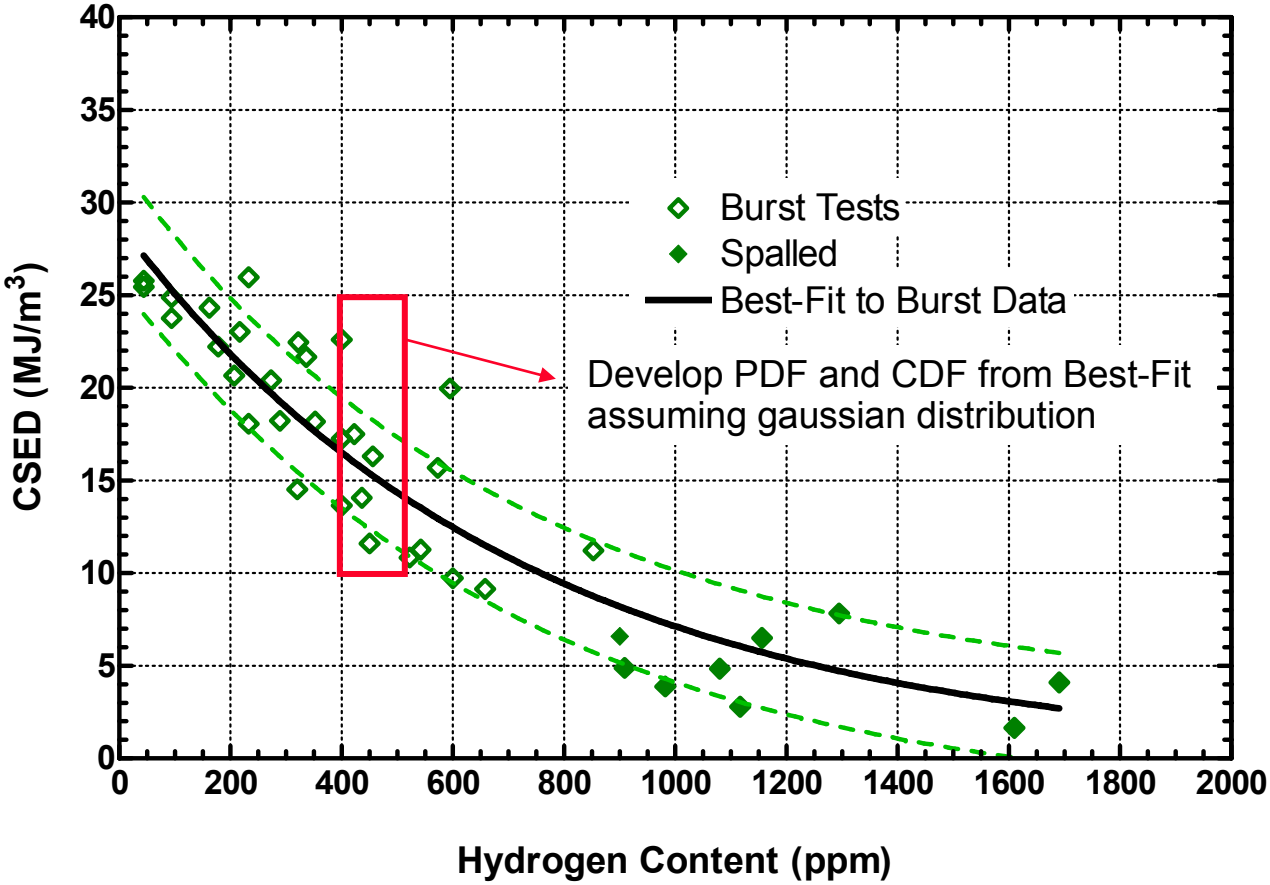
Hydrogen Content versus Burnup



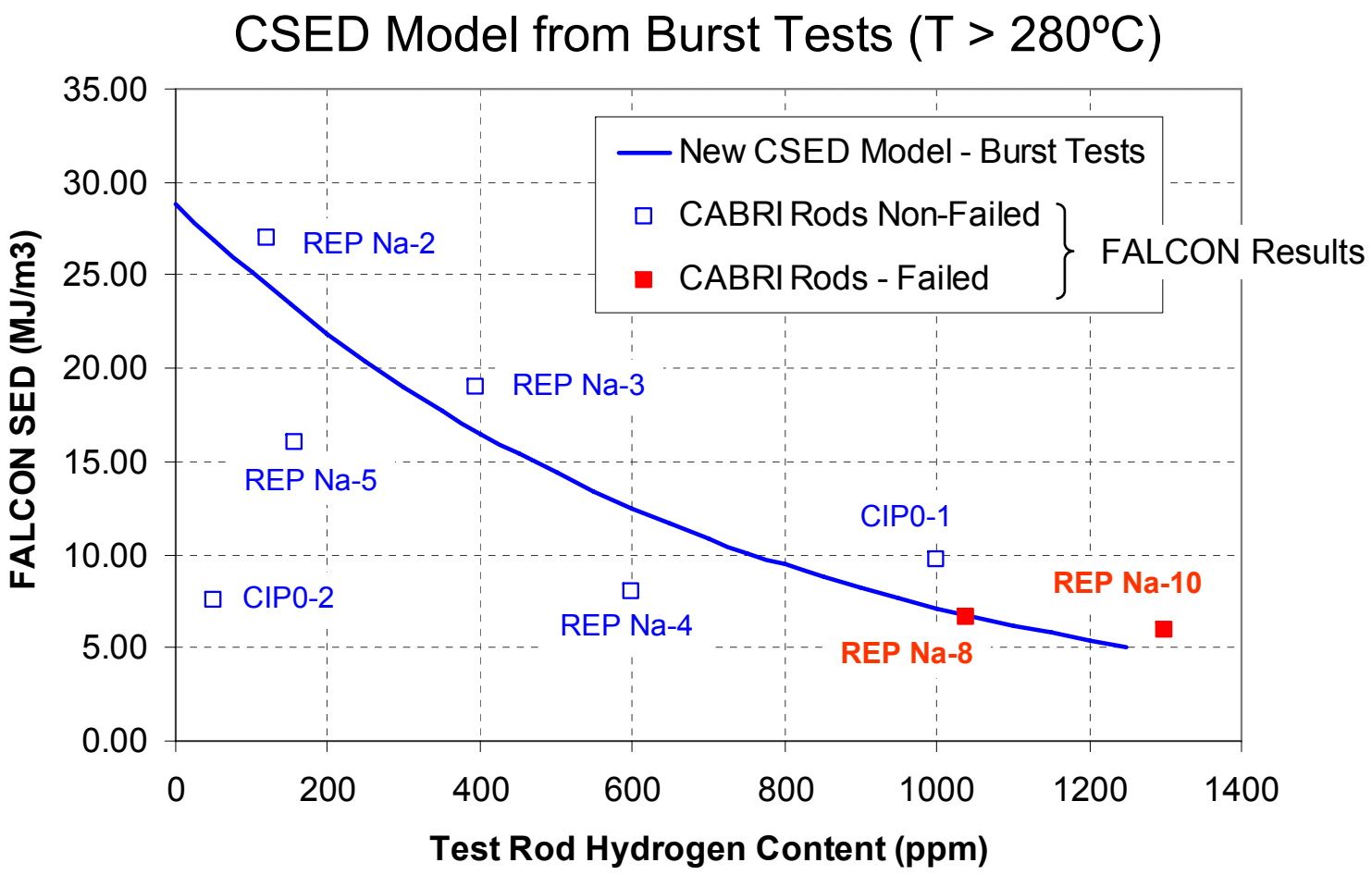
$$H(ppm) = \left[\frac{14.7 \cdot t_{ox} \cdot f_w}{C_1 \cdot W_{ox} \rho_{Zr} \left(t_{cl} - \frac{t_{ox}}{PB_{ratio}} \right)} \times 10^6 \right] \cdot f_{pu}$$



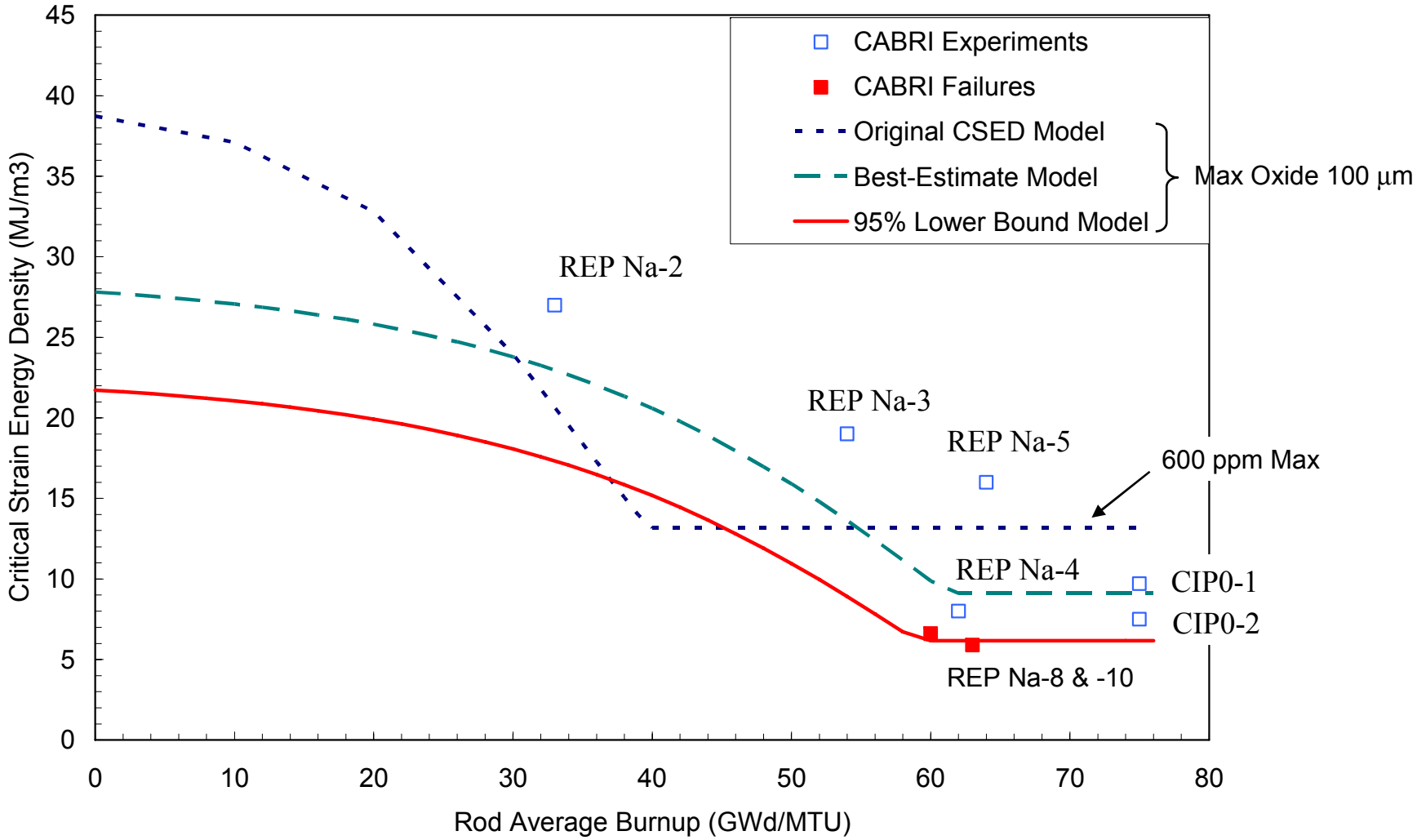
CSED versus Hydrogen Content



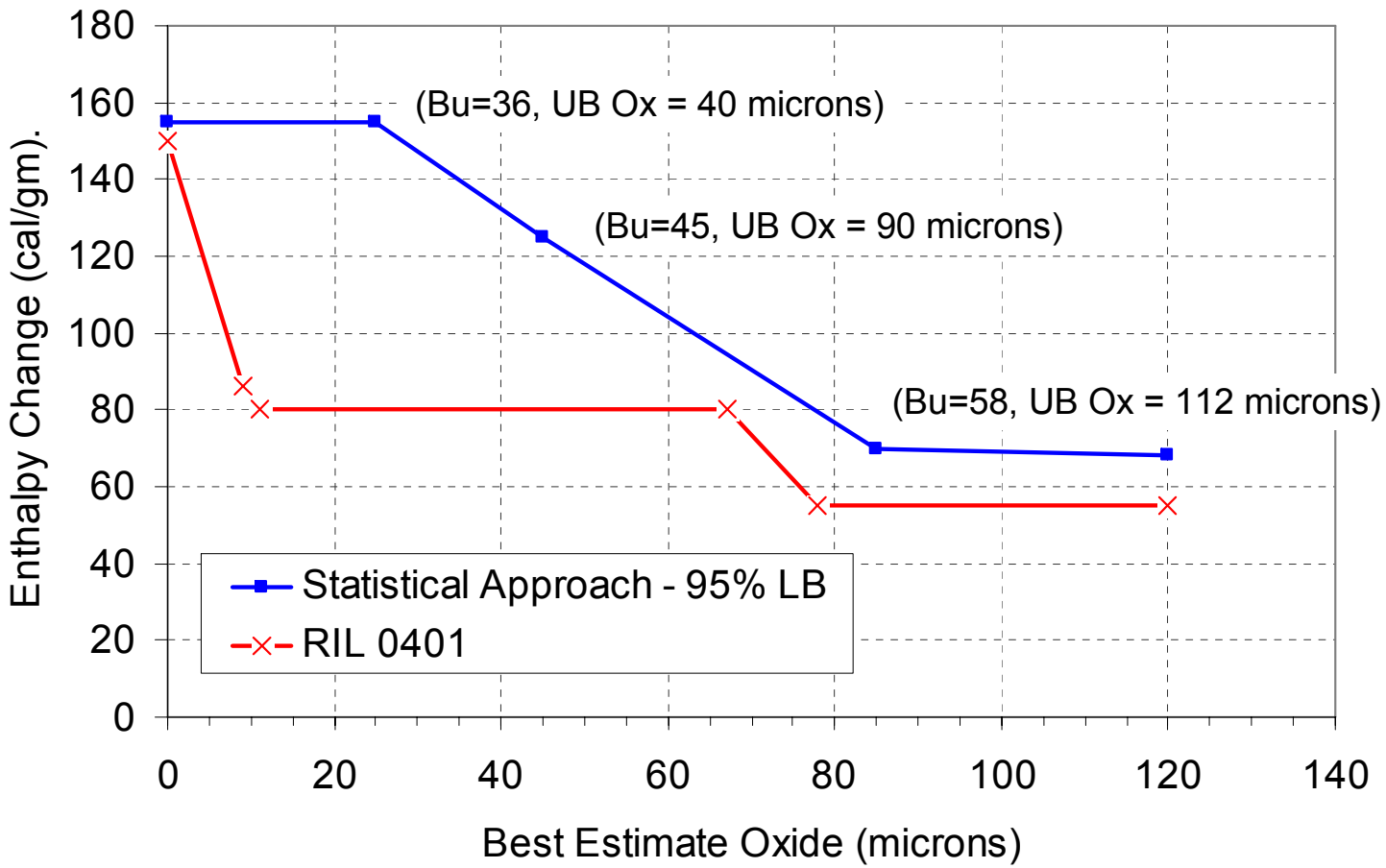
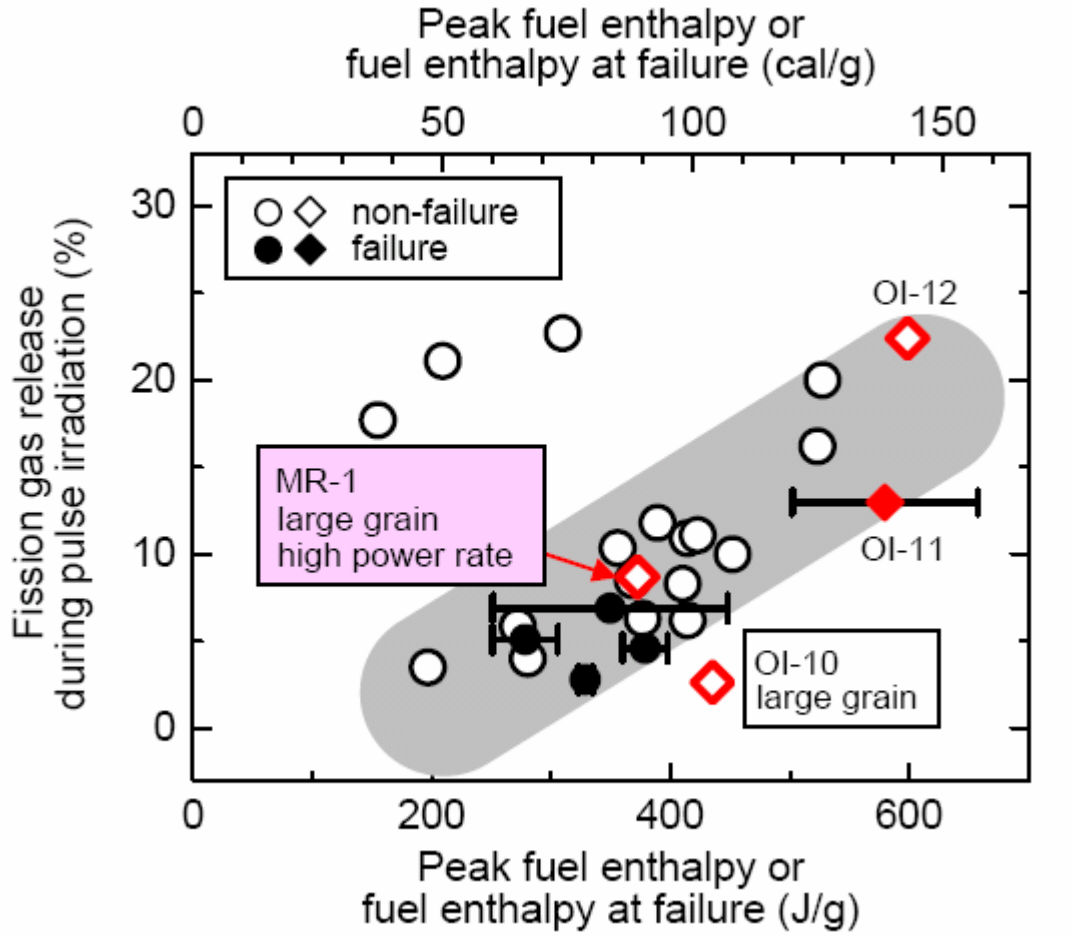
Fuel Rod Failure Prediction for CABRI Tests



Statistical CSED versus Burnup



Possible Failure Threshold as Function of Oxide Thickness



Transient Fission Gas Release