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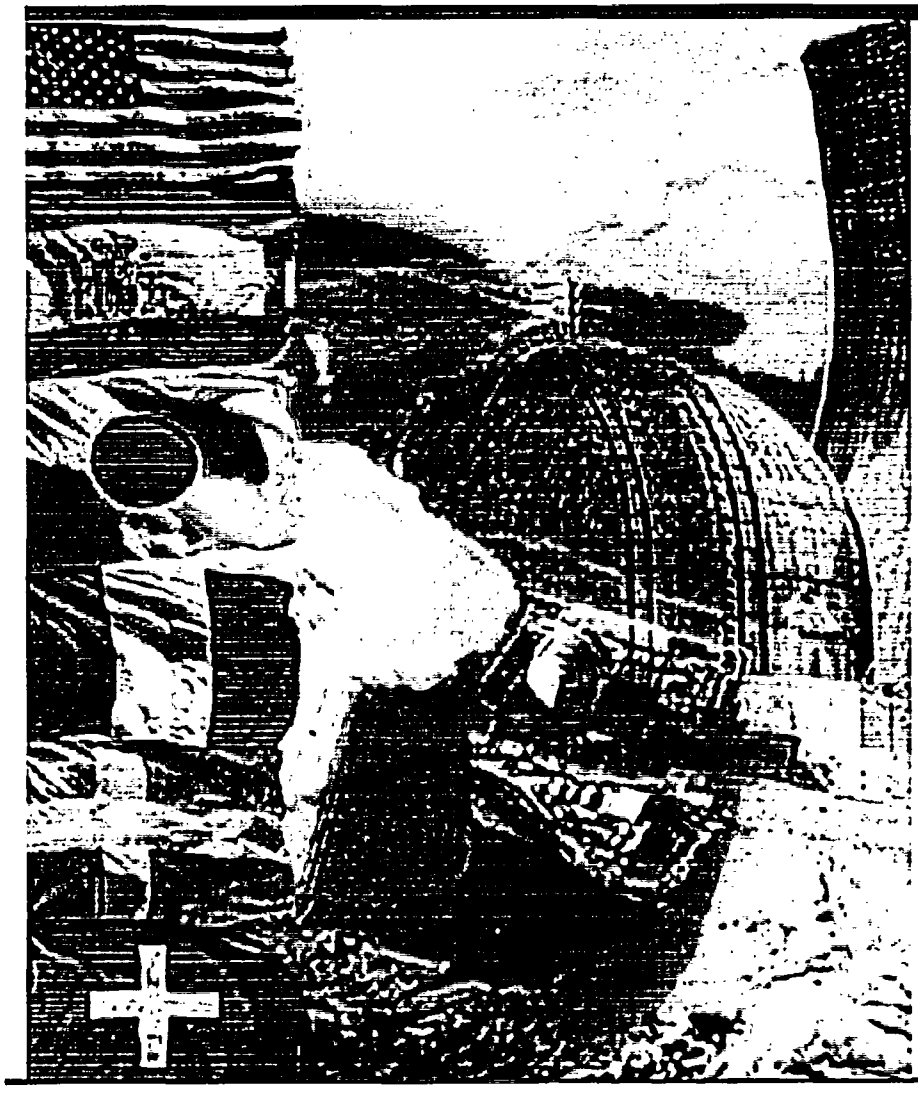

# RIA Criteria

NRR - Industry Meeting
July 7, 2004

Rosa Yang

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# Overview

- Introduction
  - Safety significance of low enthalpy failures
  - Industry response to RIA test results
  - Significant events since the topical submittal
- What are other countries considering for RIA acceptance criteria?
- Assessment of scaling method proposed in RIL 0401

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# Safety Significance of an RIA Event

- RepNa-1 and HBO-1 tests raised concerns of high burnup fuel during RIA events
  - NRC issued information letter 94-64 (August, 94)

- NRC-NRR assessment of low enthalpy failures (Nov. 1994)
  - Summarized in a memo from J. Taylor to NRC Commissioners
    - » No significant impact on public health and safety: low probability of occurrence and low power of high burnup fuel
    - » No concerns for core coolability with dispersal of solid fuel particles
    - » Increase in fuel damage fraction and radiological consequences are possible

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# Safety Significance of an RIA Event (cont'd)

- Industry assessment of low enthalpy failure threshold on plant safety (Submitted by NEI Dec. 1994)
  - Occurrence of PWR REA or BWR RDA is low ($<1 \times 10^{-6}$ /RY)
  - Continue to meet off-site dose requirements (25% of 10 CFR 100 limits) with low fuel failure enthalpy (~30 cal/gm at the time)
  - No immediate safety significance

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# Industry Response to RIA Test Results

- Review and assess experimental results from RIA-simulation experiments
  - Develop understanding of irradiated fuel behavior using experimental results, separate effects tests, and analytical evaluations
    - » Temperature, oxide thickness/H concentration and distribution and pulse width affect fuel behavior under RIA conditions
  - Identify mechanisms/processes unique to the test conditions
  - Translate data and lessons-learned to LWR RIA conditions

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# Industry Response to RIA Test Results (cont'd)

- Submitted topical reports with revised RIA acceptance criteria
  - "Region of success" (1996)
  - Burnup-dependent failure threshold and coolability limit (2002)

- RepNa-1 is an outlier and failure threshold for HBO-1 needs to be adjusted for temperature effect

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# RepNa-1 Test is an Outlier

- Since the RepNa-1 test was performed, 13 additional RIA-simulation tests have been performed in the CABRI Na-loop
  - None (spalled & un-spalled) failed at 30 cal/g
  - No failures been observed on non-spalled UO2 rods

# RepNa-1 Test is an Outlier (cont'd)

- A Task Force has been assembled to evaluate the validity of RepNa-1
  - Task Force members include international industry experts and experts from IRSN
  - The Task force has obtained significant more data and enhanced the understanding of the RIA failure mechanism
  - Due to lack of data, the Task Force was not able to reach a consensus
    - » IRSN view
    - » Other authors view
- Full report will be issued by 4 Q, 2004. A paper will be presented in the ANS LWR Fuel performance Topical Meeting in September, 2004.
- REP Na-1 has not been used in developing a failure threshold by any country

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# Events Since Submittal in April 2002

| | |
|---|---|
| • Submitted to NRR (via NEI) | April 2002 |
| • Initial review meeting with NRR | June 2002 |
| • NRR preliminary review schedule | August 2002 |
| • Request for FALCON from NRR | August 2002 |
| • ACRS fuels subcommittee meeting | October 2002 |
| • FALCON code package sent to NRR | November 2002 |
| • NRR training on FALCON | February 2003 |
| • Informal questions/comments received/discussed | March-Dec 2003 |
| • Meeting with NRR | November 2003 |

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# RIA Acceptance Criteria in Other Countries - 1

- France
  - "Safety domain" given by cladding oxide thickness, $\Delta H$, pulse width, cladding temperature (developed in late 1990s)
  - Considering failure threshold based on Industry Topical approach
- Switzerland
  - Will implement the industry proposed criteria (in the Topical report) for $UO_2$
  - Different limits for MOX
- Germany
  - Failure threshold as function of burnup and oxide thickness
  - Fuel rod fragmentation limit of 230 cal/gm

EPRI

# RIA Acceptance Criteria in Other Countries -2

- Japan
  - Failure threshold derived directly from NSRR tests (1998)
    - » Approach is very conservative - no account is given to temperature effects on cladding properties
  - Fuel rod fragmentation threshold includes burnup effects on $UO_2$ melting temperature, plutonium buildup, etc
    - » Similar to industry approach
- Spain
  - Currently evaluating the Industry Topical Report recommendations
- Sweden
  - Recently developed failure threshold using approach similar to Industry Topical approach
  - Results higher than the industry proposed values at high burnups

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# Summary

- RIA is a low probability event, criteria development needs to consider the risks
- While the exact values and approach used to develop the criteria differ in different countries, most have adopted **separate** failure and coolability limits
  - Several have adopted or will adopt the industry proposed criteria/approach
- The industry has submitted a Topical for NRC review
  - Over 100 RIA-simulation tests reviewed and analyzed
  - Analytical code benchmarked by extensive database
- Recent tests with high burnup (~75 GWd/tU) and modern cladding are consistent with the topical report recommendations
- Vendor / utility-specific topicals have or will reference the industry-developed criteria

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# Purpose of the meeting

- Understand the basis of the approach described in RIL 0401
- Provide assessment of the scaling method used to develop failure threshold in RIL 0401
  - Both recognize the importance of temperature and pulse width on RIA simulation test results
    - » Not all RIA tests are created equal
  - Use our understanding of fuel behavior to properly apply adjustment factors to RIA-simulation test data
- Provide assessment of collapsing the failure threshold and core coolability limit
  - Demonstrate that dispersal of solid fuel is not a core coolability issue
- Discuss status of the review of industry topical and schedule for completion

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# Assessment of RIL 0401 Acceptance Criteria

Robert Montgomery

NRR-Industry Meeting
US Nuclear Regulatory Commission Office
Rockville, MD
July 7, 2004



EPRI

# How to Develop RIA Failure Threshold

- Possible Approaches
  1) Mechanistic method – Industry approach described in EPRI Topical Report Submittal (EPRI 1002865, June 2002)
  2) Empirical method – NRC-RES approach described in RIL 0401
- Both approaches use RIA-simulation experiments as initial basis for fuel rod failure threshold development
  - Both recognize that results from RIA-simulation experiments cannot be used directly to develop failure threshold
  - Goal is to identify fuel enthalpy (maximum or increase) necessary to cause cladding failure under LWR conditions
    - » Function of important state variables (burnup, oxide thickness, etc.)
  - *Differences arise in how to use the RIA-simulation test data*
    - » Mechanistic method – use data to develop and validate analysis methodology
    - » Empirical method – use data adjusted with weighting factors (scaling)

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# Industry Approach to Failure Threshold Development

Mechanistic Method

- Develop analysis methodology for RIA
  - Use RIA-simulation test results (on-line and PTE) and analytical evaluations to gain understanding of fuel rod behavior
  - Identify active fuel rod deformation and failure mechanisms
    - » Develop cladding integrity model based on mechanical property tests representative of failure processes
  - Validate analysis methodology using RIA-simulation experiments
    - » Comparison to measured results (deformations, temperature, etc.)
    - » Ability to differentiate between failed and non-failed tests
- Failure threshold development for LWR conditions
  - Use validated analysis methodology as transfer function to develop failure threshold for idealized/bounding PWR HZP conditions
  - Account for important mechanisms affecting fuel rod behavior and the processes leading to cladding failure



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# NRC-RES Approach to Failure Threshold Development

Empirical method

- Data evaluation
  - Correlate experimental results to single dependent variable
    - » Cladding outer surface oxide thickness, without consideration for burnup
  - Develop weighting (adjustment) factors to compensate for differences in test conditions (temperature and pulse width only)
    - » Based on analysis methods that consider fuel rod transient behavior
- Threshold development
  - Construct failure threshold using lower-bound empirical fit to adjusted data
- Empirical method should produce results consistent with the mechanistic method if a realistic understanding of fuel behavior is used

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# Difficulties with Empirical Approach

- Does not consider the fundamental mechanisms leading to cladding failure
  - Uses RIA-simulation test results, including MOX, without interpretation
  - Ignores the effects of gap closure, fission gas enhanced PCMI, localized hydride accumulations, and wall thickness effects
- Generalizes individual rod behavior to all rods
  - $UO_2$ fuel = MOX fuel
  - Non-spalled cladding = Spalled cladding
- Approach can be biased by misinterpretation of a single rod (small data set of RIA-simulation tests)



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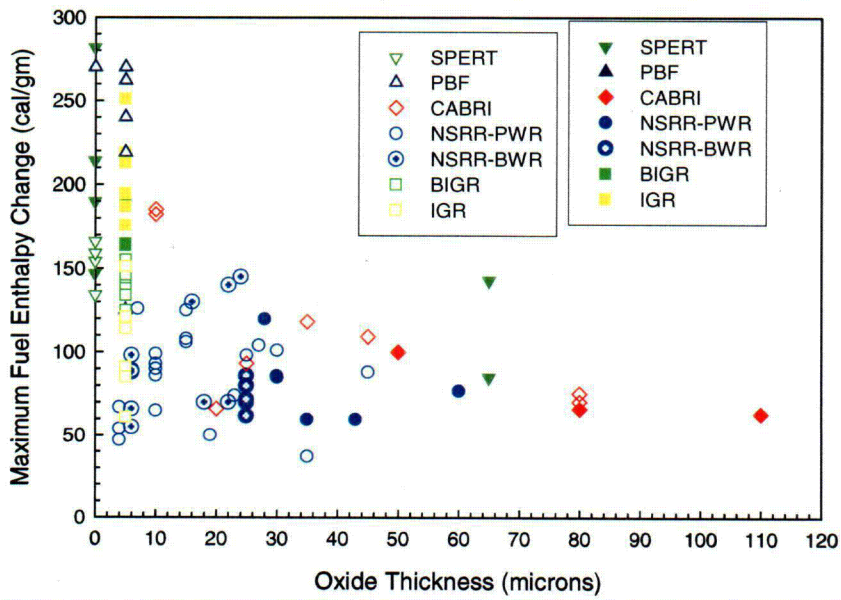
# Cladding Oxide Thickness is not the Only Parameter

RIA-simulation database plotted as function of oxide thickness






C01

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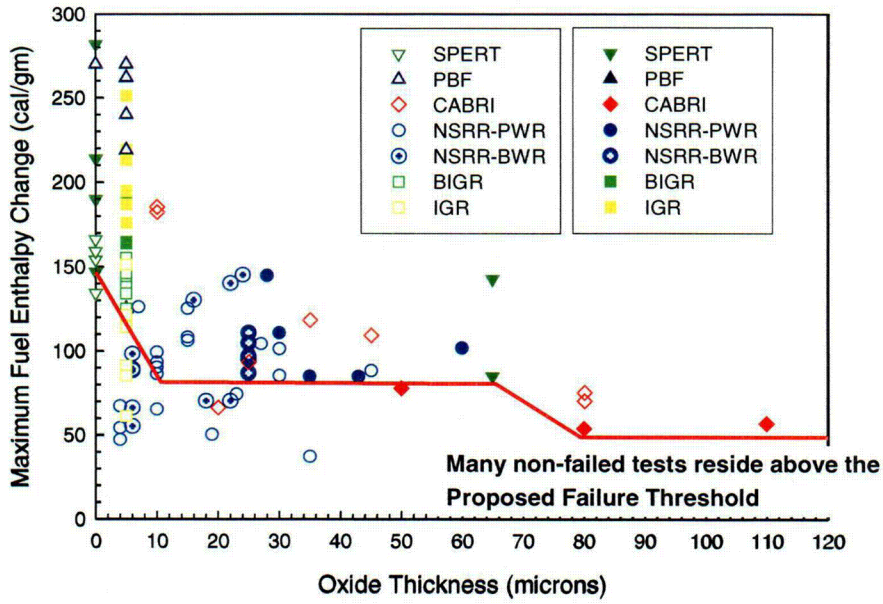
# NRC-RES Adjusted RIA Data with Proposed Failure Threshold (RIL 0401)



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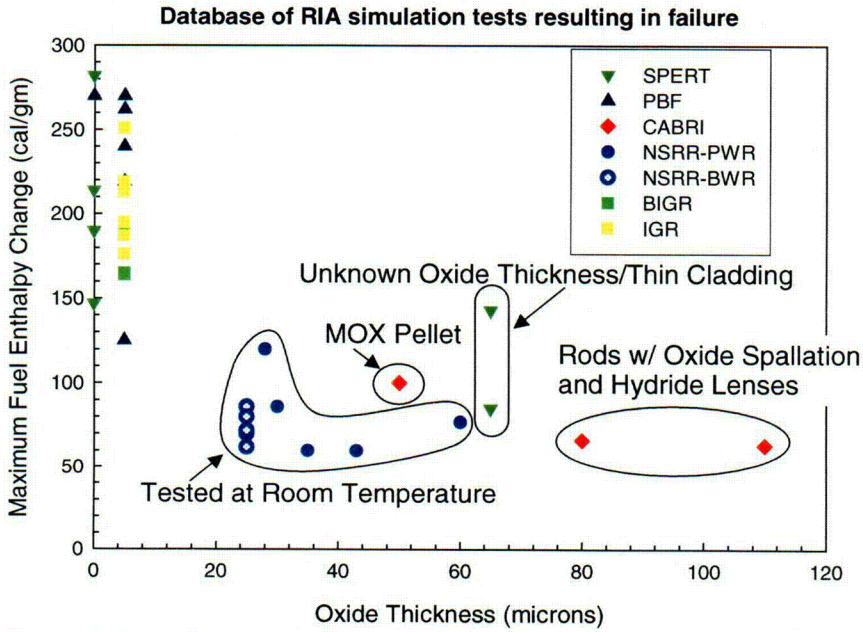
# Not all Failures were not Created Equal






C02

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## Specific Issues with NRC-RES Scaling Method

1) No consideration given to factors that influence PCMI loading
   - Pellet microstructure in MOX fuel leads to enhanced PCMI loading
   - Fuel enthalpy required to close the P/C gap is higher at low burnup
2) Effect of temperature on cladding ductility underestimated
   - Ignores improvement of ductility with increase in temperature
   - NSRR temperature adjustment insufficient (not consistent with mechanical property tests and CABRI experiments at 300°C)
3) Spalled rods not representative of non-spalled rods
   - Material ductility of non-spalled material is 2 to 5 times greater than spalled material with equivalent oxide thickness
4) Incorrect use of SPERT-CDC test rods
   - Large uncertainty in oxide thickness for these rods
   - SPERT-CDC test rods used extra-thin cladding material



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## PCMI not only function of fuel enthalpy

- Fuel enthalpy required to initiate PCMI loading is dependent on pellet-cladding gap size – burnup effect
  - Pellet swelling, relocation, and cladding creep cause residual gap size to decrease with burnup
  - Fuel enthalpy of 130 cal/gm produces ~2 times smaller PCMI load at low burnup (enthalpy needed to close the gap)
- Fission gas bubble inventory enhances pellet expansion process in MOX fuel
  - Higher PCMI loading as compared to $UO_2$ fuel at the same fuel enthalpy
  - Use of MOX rod REP Na-7 not appropriate for $UO_2$ fuel application

> Fuel enthalpy required to produce sufficient PCMI loading to fail the cladding is a function of burnup and pellet type, as well as oxide thickness ratio

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# Comparison of MOX and $UO_2$ PIE Observations

| | Maximum Fuel Enthalpy (cal/gm) | Maximum Residual Hoop Strain (%) | Fuel Type |
|---|---|---|---|
| REP Na-2 | 199 | 3.5 | $UO_2$ |
| REP Na-9 | 197 | 7.2 | MOX |
| REP Na-3 | 124 | 1.8 | $UO_2$ |
| REP Na-6 | 133 | 2.6 | MOX |
| REP Na-5 | 108 | 1.1 | $UO_2$ |

[REP Na-2 (UO2) and REP Na-9 (MOX) experienced the same peak enthalpy yet residual strain in MOX is twice as large]

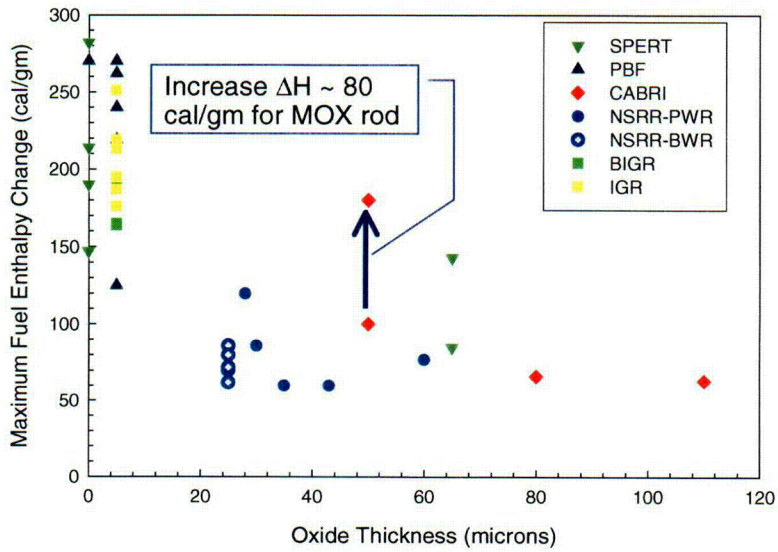
Enhanced pellet expansion and PCMI loading in MOX pellets caused by larger fission gas bubble inventory



EPRI

# CABRI REP Na-7 MOX Adjustment
## (Issue # 1)

Fuel enthalpy required to produce the same PCMI loading (and fail the cladding) as a $UO_2$ pellet






C03

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# Temperature: The most important adjustment factor

- Main difference between CABRI and NSRR tests is initial coolant temperature (280°C vs. 20°C)
  - Affects cladding performance during PCMI loading
- Temperature correction for NSRR BWR and PWR rods inconsistent with CABRI results and mechanical property data
  - CABRI Na-3, 4, 5, 6, and CIPO-1 tests were non-failed at 300°C up to ΔH of ~120 cal/gm
  - Mechanical property tests (Daum et al., Olivier) show fracture strain increase by factor of 2 between room temperature and 300°C
  - Mechanical property tests on BWR cladding show dramatic improvement above 200°C (Studsvik EDC tests with highly non-linear transition)

Improvement in ductility justifies much larger adjustment factor on fuel enthalpy change (>60 cal/gm)



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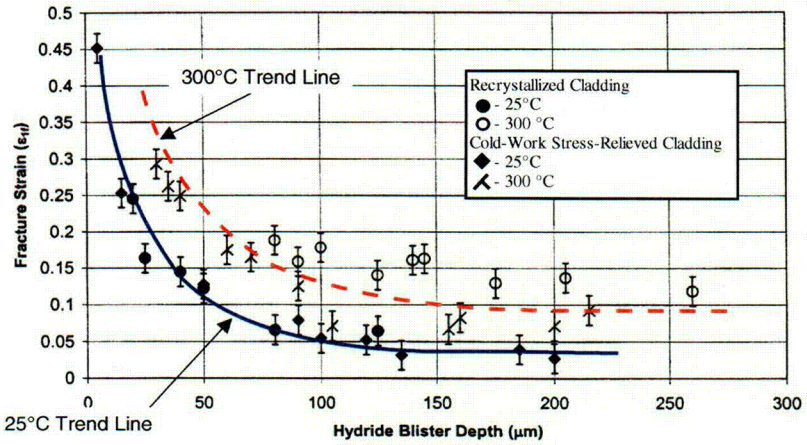
# Temperature Increases Strain to Fracture

Plane-Strain Ring Tests on Unirradiated, Pre-hydrided Cladding




Higher temperature has twice the fracture strain



C04

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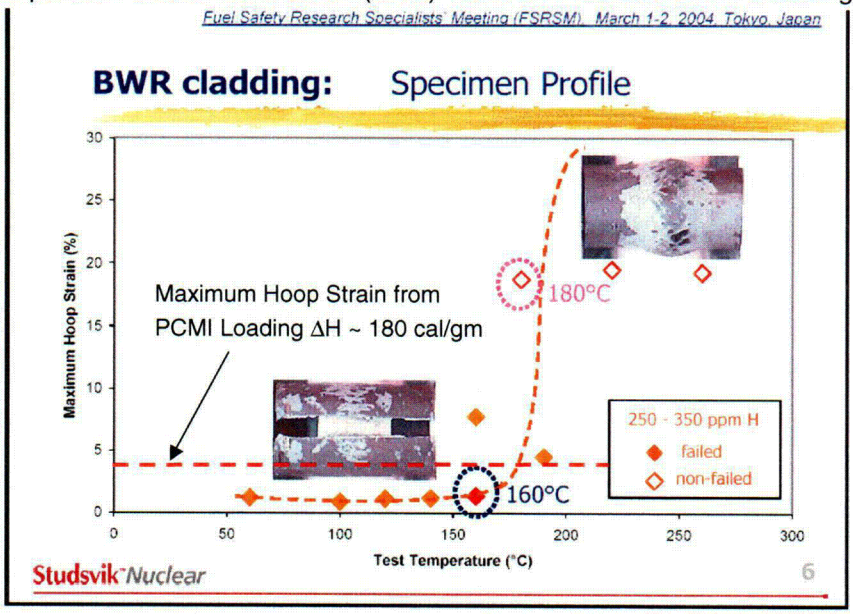
# Temperature Increases Maximum Deformation

Expansion Due to Contraction (EDC) Tests on Irradiated BWR Cladding



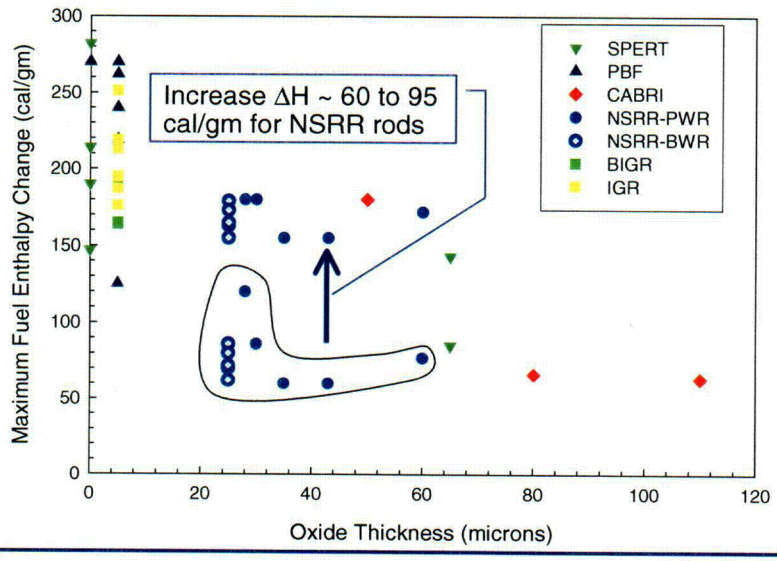



EPRI

# NSRR Temperature Adjustment
## (Issue # 2)

Temperature effect on cladding ductility for NSRR rods

⇒ Increase fuel enthalpy change 60 to 95 cal/gm






C05

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## Spalled Rods not the same as Non-Spalled Rods

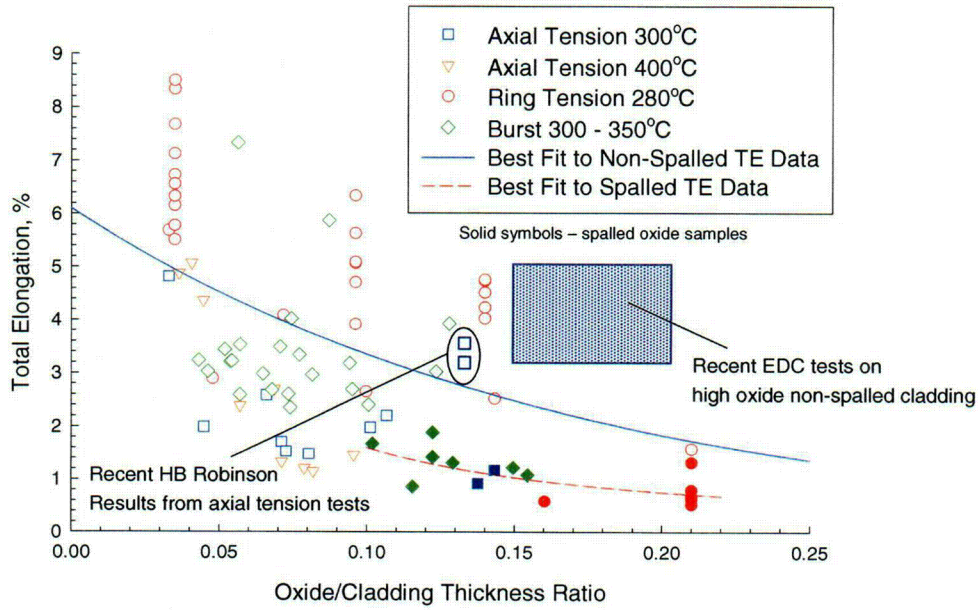
- Not Appropriate to use CABRI REP Na-8 and REP Na-10
  - Generalizes spalled material behavior to non-spalled cladding
  - Does not recognize the impact of localized hydride accumulations to act as flaws
- Non-spalled cladding material demonstrates markedly different results in RIA-simulation tests and mechanical property tests
  - None of the non-spalled $UO_2$ rods failed in CABRI – all spalled rods failed
  - High oxide non-spalled cladding show factor of 2 to 3 times higher ductility than equivalent spalled cladding

Spalled rods are unique and behavior is not representative of typical cladding material – results cannot be extrapolated



EPRI

## Elongation Data - High Burnup/High Oxide Cladding



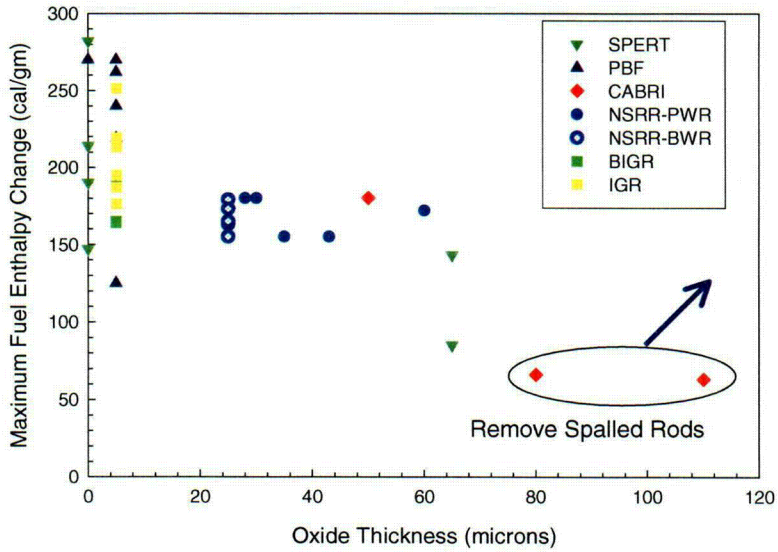



C06

EPRI

# Spalled Cladding Adjustment
## (Issue # 3)

Threshold applicable to non-spalled rods with oxide thickness less than or equal to 100 microns



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# CDC-SPERT Test Rods

- Large uncertainty in outer surface oxide thickness
  - No direct measurement of oxide thickness
  - NRC used cladding diameter change as the oxide thickness
  - Much higher oxide thickness (> 100 microns) obtained from metal loss calculated using diameter change and Pilling-Bedworth ratio
- Test rods used extra-thin cladding material (~500 μm)
  - Large oxide to cladding thickness ratio
  - Equivalent to > 130 microns oxide thickness for current commercial reactor fuel designs
- Temperature adjustment should also be applied
  - Tests conducted at room temperature

A much larger oxide thickness should be used for CDC-SPERT tests

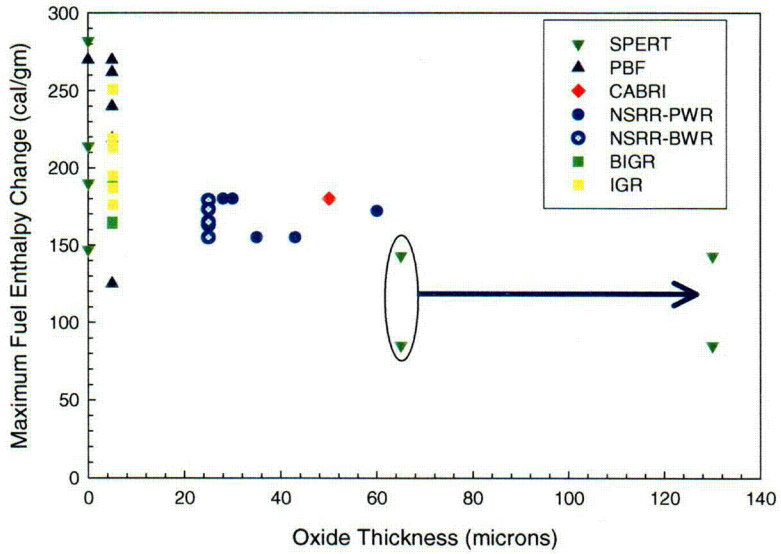


C07

EPRI

# CDC-SPERT Test Adjustment
## (Issue # 4)

Increase cladding oxide thickness for high oxide CDC-SPERT Tests



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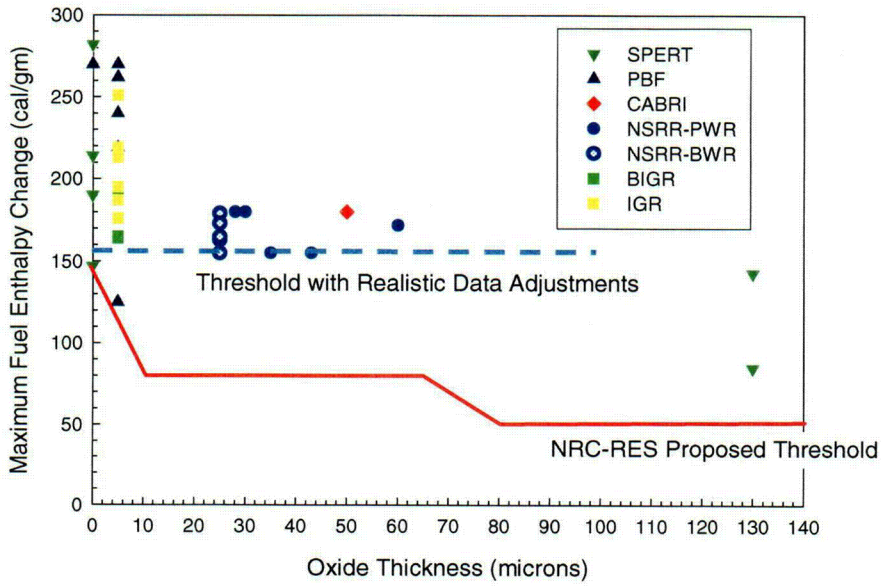
# Database with Corrected Data Adjustments






C08

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# Industry Approach to Coolability Limit

- Coolability limit separate from failure threshold
  - Allow energy deposition beyond cladding failure
  - Establish limit to preclude incipient pellet melting
    - » Dispersal of molten pellet material can lead to important fuel-coolant interaction and mechanical energy generation
  - Fuel enthalpy limit as function of burnup based on experimental results and analytical evaluations
- Programs are underway to evaluate the consequences of fuel dispersal for high burnup fuel
  - Experimental programs at JAERI and CABRI Water Loop Project
  - Engineering evaluations of the consequences associated with solid fuel dispersal
  - Results of these programs will confirm the benign consequences of solid fuel dispersal



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# Post-failure Behavior of High Burnup Fuel

- Irradiated fuel has shown dispersal of non-molten fuel particles following cladding failure in some tests
  - Changes with irradiation in the local power peaking near pellet periphery and the pellet microstructure
  - Factors that affect dispersal of non-molten (solid) fuel particles include pulse width, clad failure during energy deposition, and burnup
    - » No fuel dispersal following cladding failure for any tests with pulse widths greater than 10 milliseconds in high burnup $UO_2$ fuel
- Experimental observations
  - Dispersal of < 10% of pellet material adjacent to cladding crack region (primarily from pellet periphery)
  - Solid particles with sizes greater than 10 microns
  - Lower thermal to mechanical energy conversion ratios as compared to molten material
    - » Large particle size (>10 microns)
    - » Lower efficiency of heat transfer to coolant

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# Industry Assessment of Solid Fuel Dispersal

- Interpretation required to apply experimental results to LWRs
  - Amount of fuel dispersal is influenced by sample geometry
    - » NSRR experiments biased by end effects in short (6") rods for several cases (fracture of end caps by crack propagation)
  - Mechanical energy conversion in tests not representative of LWR conditions
    - » Fuel volume to coolant volume ratio in test exaggerates fuel-coolant interaction effects by an order of magnitude compared to PWR conditions
- Solid fuel dispersal is not a coolability issue
  - Limited amount of material and inefficient thermal to mechanical energy conversion produces minimal fuel-coolant interaction
    - » Small pressure pulse generation (< 200 psi) under reactor conditions
  - Limited amount of material and small particle size minimizes the potential for fuel material collecting at grid spacer locations
    - » Not possible to develop coolant flow blockage



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# Main Issue is Dispersal of Molten Fuel

- Consequences of molten fuel dispersal during prompt energy deposition may be significant
  - Data indicate that fuel melting during energy deposition can lead to loss of fuel rod geometry and molten fuel-coolant interaction
  - Mechanical energy generation from molten fuel-coolant interaction can lead to coolant pressure pulses
  - Large coolant pressure pulses may lead to disruption of core geometry, provided sufficient energy is deposited
- Current limit (280 cal/gm limit) established to prevent dispersal of molten fuel
  - Established based on tests with unirradiated fuel
  - Test data in CABRI and NSRR on irradiated fuel continue to support high coolability limit (>200 cal/gm at 30 GWd/tU)
  - Requires adjustment to account for changes in $UO_2$ melting temperature at higher burnup

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# Development of Coolability Limit

1) Industry ⇒ Limit maximum fuel enthalpy to preclude incipient fuel pellet melting
   - Established using analytical approach – calculate fuel enthalpy required to reach local pellet melting temperature
   - Decreases with burnup due to changes in $UO_2$ melting temperature and local pellet temperature
   - Consistent with high energy RIA tests and coolability limits established by others

2) NRC-RES ⇒ No fuel rod failures allowed
   - Established to prevent the dispersal of solid fuel particles



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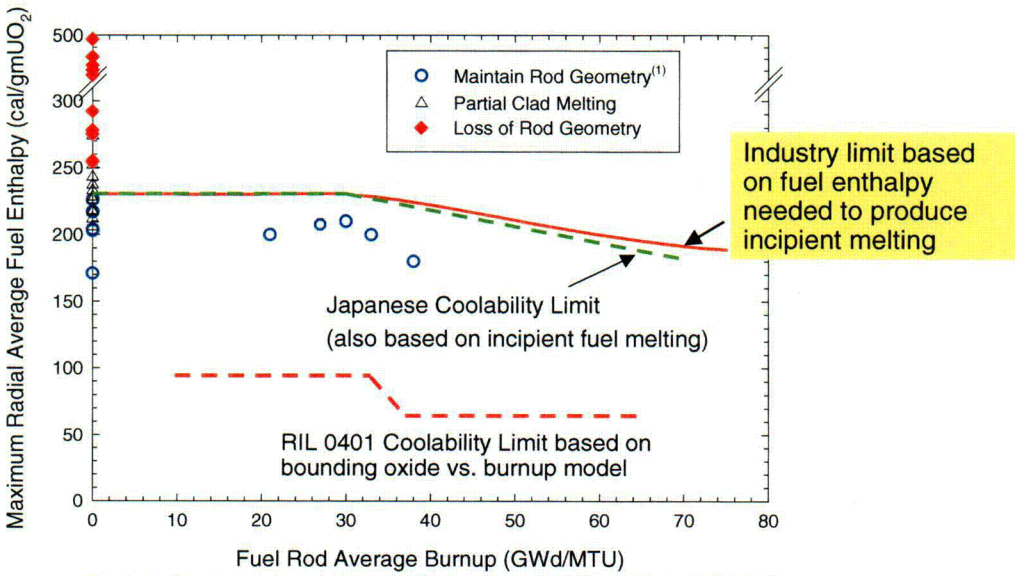
# Coolability Limit as Function of Burnup




1. Sugiyama, T. and et. al. Journal of Nuclear Science and Technology, Vol 37, No 10, Oct 2000



C09

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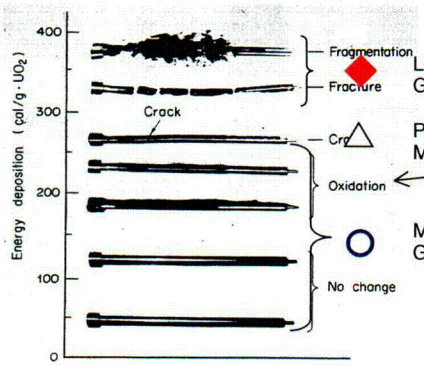
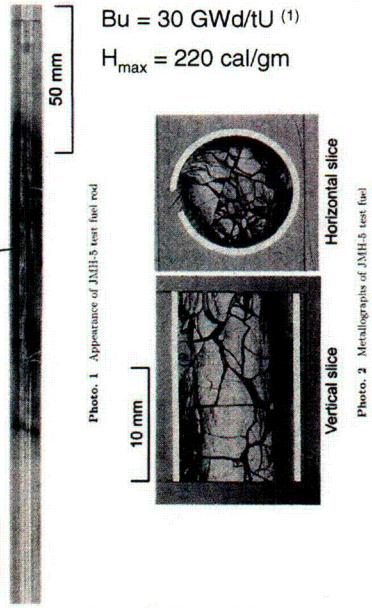
# Post-Test Condition with Fuel Dispersal

Unirradiated Tests in NSRR (2)




Bu = 30 GWd/tU (1)

$H_{max}$ = 220 cal/gm




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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# Japanese Coolability Limit

- Limit consequences of mechanical energy generation and fuel rod fragmentation
  - Peak fuel enthalpy must not exceed 230 cal/gm – $\Delta E$
  - The term $\Delta E$ accounts for burnup effects on $UO_2$ melting temperature, plutonium build up, etc.
- Justification included evaluation of solid fuel material dispersal following PCMI failure
  1) Mechanical energy generated from PCMI failures is much less than the maximum absorbable energy of the reactor vessel
  2) Pressure pulse generation does not lead to water hammer
  3) Dispersed fuel remains coolable based on Lipinski model for boiling and dryout in particle beds

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# Differences in NRC-RES and Industry Approaches

- Industry Approach: Coolability limit based on fuel melting
  - Represents upper bound of high energy tests in CABRI and NSRR
  - Tests with loss of rod geometry above the limit (at zero burnup)
  - Loss of rod geometry not observed in database of irradiated $UO_2$ RIA-simulation tests (maximum fuel enthalpy levels between 180 and 220 cal/gm and burnup of 38 GWd/tU)
  - Close agreement with Japanese limit
- NRC-RES: Coolability limit based on fuel dispersal (RIL 0401)
  - Many tests that maintained rod geometry reside above the limit
  - Unrealistic lower bound, over-conservative by a factor of 2 or more



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# Application to PWR HZP REA

- Use acceptance criteria to assess neutron kinetics results for plant calculations
  - W 3-Loop and 4-Loop plants
  - 3-D neutron kinetics methods using conservative assumptions to bound uncertainties in rod worth
  - Radial average peak fuel enthalpy as function of burnup
- Converted NRC-RES limit from oxide dependence to rod average burnup dependence
  - Used bounding oxide vs. burnup curve from EPRI Topical Report
- NRC-RES limit exceeded in both plant cases
  - Requires plant redesign or improved analysis methods

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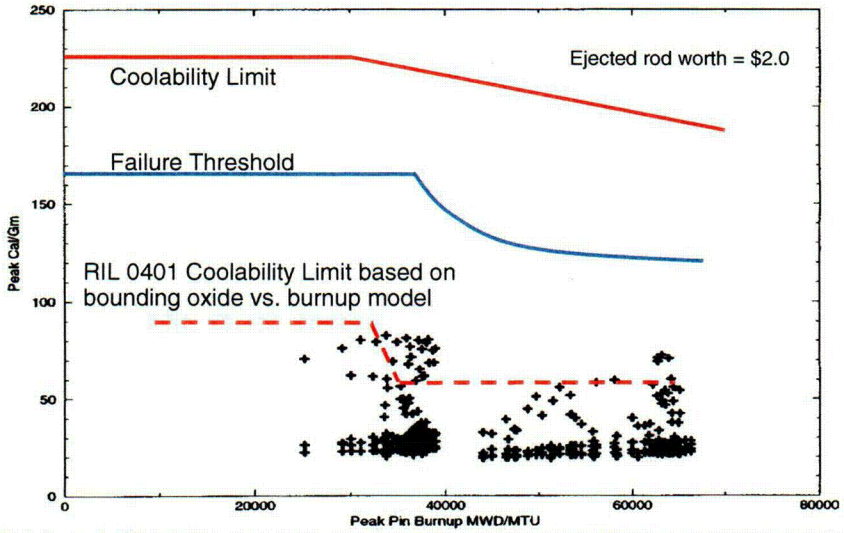
# Application to PWR HZP REA

## Licensing 3-D Neutron Kinetics Results (W 4-Loop Plant)[3]




3. Risher D., et. al., "Generic Assessment of the High Burnup Reactivity Insertion Accident Issue in Westinghouse PWRs," Proceedings of the Fifth International Topical Meeting on Nuclear Thermal-Hydraulics, Operations,and Safety, Beijing, China, April, 1997.



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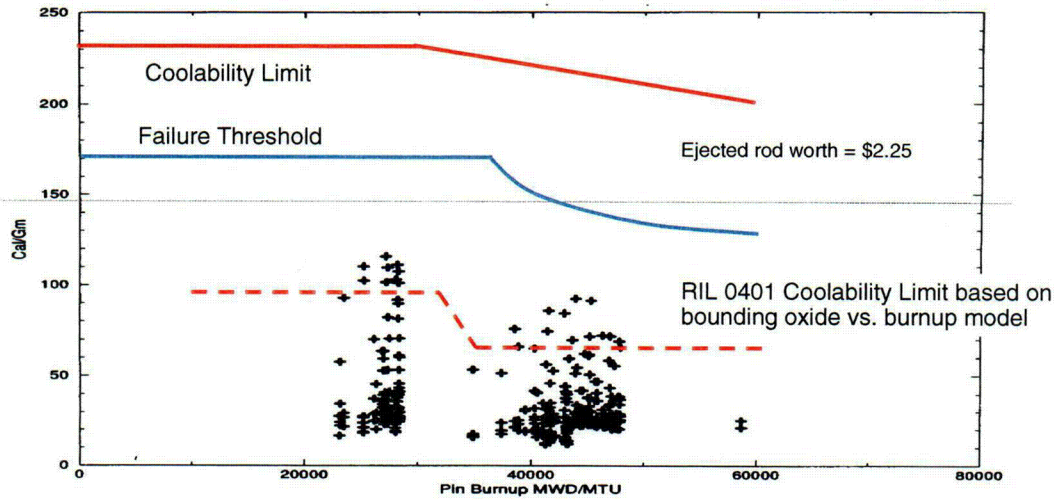
# Application to PWR HZP REA (cont.)

## Licensing 3-D Neutron Kinetics Results (W 3-Loop Plant)[4]




4. Ray, S., et.al., "A BEST-ESTIMATE ASSESSMENT OF ROD EJECTION FUEL DUTY IN PWRs," Proceedings of the CSNI Specialists Meeting on Transient Behavior of High Burnup Fuel, Cadarache France, September 12-14, 1995, Report NEA/CSNI.R(95) 22, 1996.



C11

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## Conclusions: Failure Threshold

- Use of a scaling approach requires realistic understanding of fuel behavior under RIA conditions
  - Adjustments to RIA-simulation test database required for MOX fuel, initial temperature in NSRR tests, spalled cladding, and thick oxide/thin-walled cladding
- Proper scaling approach produces equivalent failure threshold as in Industry Topical Report
  - Demonstrates consistency in our understanding of the factors leading up to cladding failure
  - Confirms the mechanistic approach to develop the failure threshold for RIA events



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## Conclusions: Coolability limit

- Database of RIA-simulation tests demonstrate no loss of fuel rod geometry up to 38 GWd/tU and fuel enthalpy up to 220 cal/gm
  - Prevention of fuel melting is sufficient to ensure a coolable core geometry
  - Consistent with Industry-proposed limit
- No justification for prohibiting fuel failures in RIA event
  - Database of RIA tests does not support this approach
  - Solid fuel dispersal observed in RIA tests does not constitute loss of rod geometry or loss of coolability
  - Evaluations show no consequences for core coolability
- Overly conservative to restrict RIA events to no fuel failures
  - Will have impact on plant operations even with improved neutron kinetics methods