Lower RIA Limits for high burnup Fuel ?

- CABRI RepNa-1 test (November, 1993) raised concerns about fuel failure limits and fuel dispersal for high burnup fuel
  - High burnup (64 GWD/T) Zr-4 cladding
  - Oxide=80 µm with extensive spallation
  - 9.5 ms pulse width
  - Reported failure level ~30 cal/g
  - Fuel dispersal observed

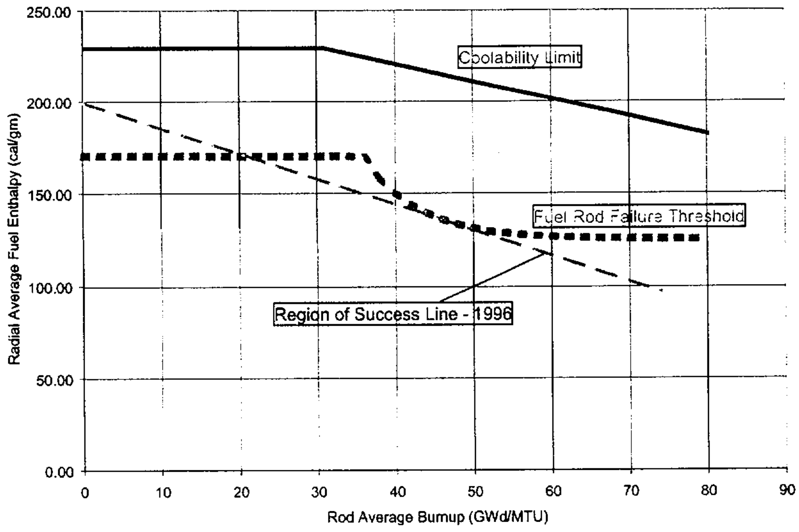
Significant Progress Made Since 1994

- Many RIA-simulation tests performed since 1994
  - 11 CABRI tests from France
  - 36 tests NSRR tests from Japan
  - RepNa-1 results never duplicated
- Considerably more knowledge and data available
  - Good understanding and agreement from conferences and published papers on the RIA failure mechanisms
    - Data are consistent if accounted for differences in key parameters
  - Analytic tools capable of predicting RIA response are available
    - FALCON, SCANAIR, and FRAPTRAN
    - Model calculations are consistent with experimental results
  - Experiments/analysis of fuel/coolant interactions

ATTACHMENT 2

Significant Progress Made since 1994 (cont'd)

- First industry evaluation of RIA (EPRI report, 1996)
  - Core coolability limit of 230 Cal/g
  - Burnup-dependent failure limit based on "Region of Success"
  - Many countries have used the "Region of Success"
- New, less conservative, more realistic approach appropriate. The industry has:
  - Used FALCON, mechanical property data and RIA simulation tests to develop the failure limit
  - Adopted "no incipient melting" to ensure coolability



RepNa-1 Task Force Formed

- RepNa-1 is unique
  - Much lower failure enthalpy compared to other RepNa tests
  - Failure did not occur at peak power location
  - None of the codes can explain the test results
    - Reported failure enthalpy is so low that the clad is in the elastic range
- Concerns raised:
  - Pre-existing defects
  - Unique pre-conditioning conditions
  - Accuracy of the timing of failures (interpretation of signals)
    - Failure at a small fraction of deposited energy
  - Microstructure
- RepNa-1 Task Force formed within the CABRI International Project in October, 2000
  - To perform an objective investigation of RepNa-1

Two major areas investigated by the RepNa-1 Task Force

- Uncertainties in signal analysis: microphones, different systems to record flow meters and pressure sensors have been used to record the timing (and enthalpy level) for rod failures & fuel dispersal
  - The reported low value was based on microphone signals
    - The acoustic signals could come from events other than failures, as demonstrated in RepNa-8
  - Significant uncertainties exist for pressure sensors and flow meters
    - Conflicting failure time from different systems
  - Current conclusion is that the failure occurred **between 30-60 cal/g** (NOT the 30 cal/g reported)

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Two major areas investigated by the RepNa-1 Task Force (Cont'd)

- Microstructures investigation
  - Good progress made, relevant information being collected
  - Expected to complete the investigation by early, 2003
  - Pre-test defect is being investigated
- RepNa-1 results are unique and should not be used until the completion of the RepNa-1 Task Force investigation

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Interactions with NRC

- Industry-wide meeting
  - NRC presentations on high burnup issues - 11/97
- ACRS Fuels Subcommittee Meeting
  - Industry interpretation of RIA experiments – 4/98
- Industry/NRR meetings
  - RFP Fuel burnup extension strategy – 1/99
  - RFP process to establish licensing criteria for fuel burnup extension (Industry Guide Document) – 3/99
  - Examples of Industry review process (IG sections) – 2/00
  - Approach to develop revised RIA criteria – 12/00
  - NSRC meeting presentation on RIA criteria-10/01
  - Telecon with NRR about submittal of RIA topical - 3/25/02
  - RIA Topical submitted to NRR by NEI - 4/17/02

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Bases for RIA Fuel Failure and Core Coolability Acceptance Criteria

Robert Montgomery
Nicolas Waeckel
Rosa Yang

EPRI/NEI/NRC Meeting
NRC Offices
Washington, D.C.
June 6, 2002

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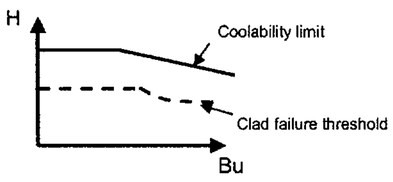
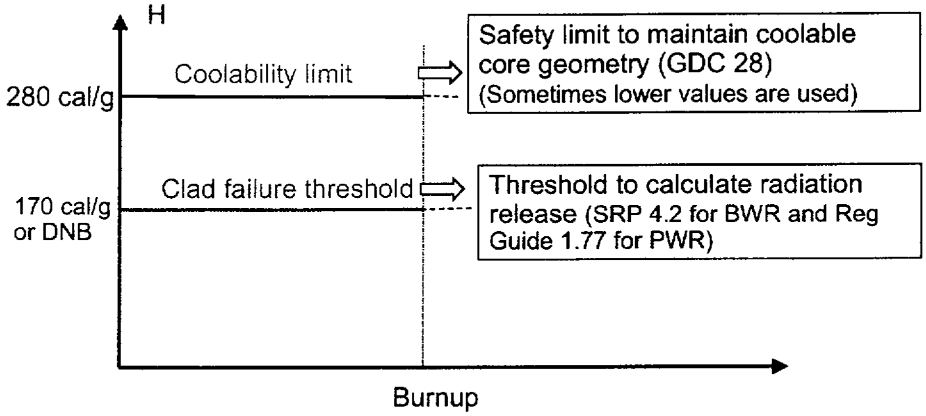
Presentation Outline

- Regulatory basis
- Database of RIA-simulation tests
  - integral tests and test conditions
- Fuel Rod Failure
  - Clad failure mechanisms at low and high burnup
  - Clad failure model for PCMI
  - Revised fuel rod failure threshold
- Core Coolability
  - Core coolability issues
  - Revised core coolability limit
- Summary



Regulatory background

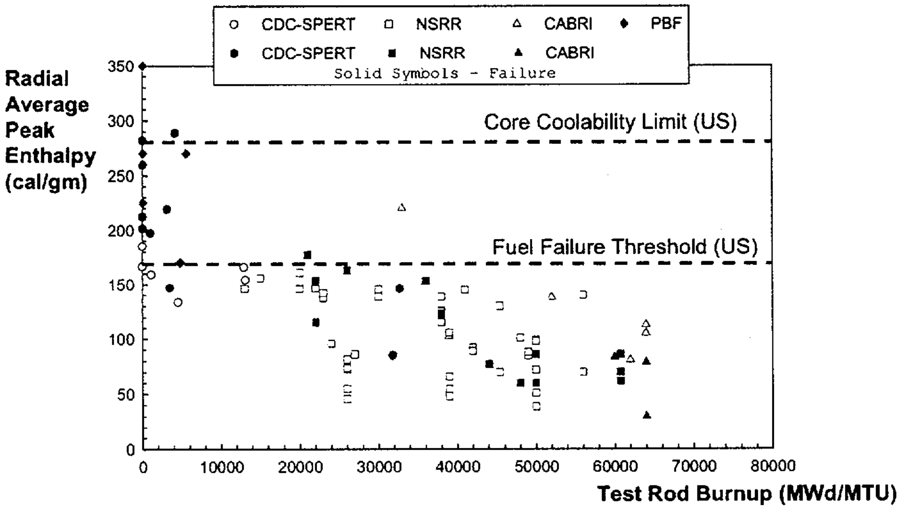
- Separate clad failure threshold and coolability safety limit



Safety limit to maintain coolable core geometry (GDC 28) (Sometimes lower values are used)

Threshold to calculate radiation release (SRP 4.2 for BWR and Reg Guide 1.77 for PWR)

Database of RIA-Simulation Tests on Irradiated UO_2 Fuel



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Test Conditions vs. LWR

	SPERT-CDC	NSRR	CABRI	LWR
Number of Tests	> 15	> 50	12	
Coolant Conditions				
Type	Stagnant Water	Stagnant Water	Flowing Sodium	Flowing Water
Temp (°C)	25	25	280	280 - BWR 290 - PWR
Pressure (atm)	1	1	3	70 - BWR 150 - PWR
Pulse Characteristics				
Full-Width Half Max. (msec)	13 to 31	4.5 to 6.6	10 natural 30-80 pseudo	25 to 90
Deposited Energies (cal/gm)	160 to 350	20 to 200	100 to 200	TBD

⇨ Need analytical tools to assess tests results and compare to LWR conditions

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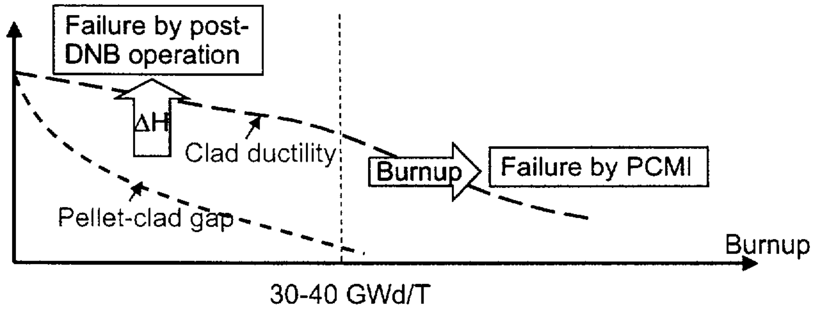
Clad failure mechanisms

- Based on over 100 RIA-simulation tests, the clad failure mechanisms are:
  - Low Burnup: high temperature failure caused by post-DNB operation (clad oxidation / embrittlement or clad ballooning)
  - High Burnup: Pellet Clad Mechanical Interaction (PCMI) combined with loss of clad ductility



Clad failure mechanisms at high burnup

- Clad failure mechanism is PCMI resulting from fuel thermal expansion and fuel matrix fission gas swelling
  - ⇨ Cladding **ductility** is the key determining factor
  - ⇨ Conclusion of the PWR RIA PIRT Report (NUREG/CR-6742)
- Fuel rod failure depends mainly on cladding ductility NOT on burnup
  - Corrosion/hydriding and fuel duty define clad residual ductility
  - Spalled rods have significantly less ductility than non-spalled rods
    - » CABRI database shows NO failure up to 64 GWd/TU for non-spalled rods

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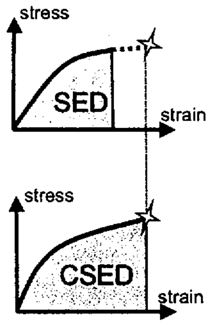
Clad Failure Model for PCMI Conditions



- Strain Energy Density (SED) is a measure of loading intensity on the cladding
  - SED is a calculated response parameter, based on integrating stress and strain
  - Addresses the effects of strain rate, temperature and stress biaxiality
- Critical SED is a measure of cladding failure potential or cladding residual ductility
  - CSED is determined from mechanical property tests
  - depends mainly on H level, temperature and materials
- Cladding failure occurs when SED reaches the CSED for a given clad material

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Extensive Database of Cladding Mechanical Properties

Program	Fuel Type	Max. Bu (GWd/tU)	Max. Fast Fluence (n/cm^2)	Range of Oxide Thickness (μm)	Temperature Range (K)	Strain Rate (/sec)
ESEERCO Hot Cell Program on Zion Rods						
Burst	15x15	49	9.4x10^{21}	15 - 25	588	2x10^{-5}
ABBCE-DOE Hot Cell Program on Fort Calhoun Rods						
Burst	14x14	53	8x10^{21}	30 - 50	588	6.7x10^{-5}
EPRI-B&W Hot Cell Program on Oconee-1 Rods						
Axial Tension	15x15	25	5x10^{21}	< 20	616	8x10^{-5}
Ring Tension						
Burst						
EPRI-ABBCE Hot Cell Program on Calvert Cliffs-1 Rods						
Axial Tension	14x14	68	12x10^{21}	24 - 110‡	313 - 673	4x10^{-5}
Ring Tension				24 - 115‡	573	4x10^{-5}
Burst				36 - 110‡	588	6.7x10^{-5}
ABBCE-DOE Hot Cell Program on ANO-2 Rods						
Axial Tension	16x16	58	12x10^{21}	24 - 46	313 - 673	4x10^{-5}
Burst				24 - 46	588	7x10^{-5}
EdF-IPSN PROMETRA Program						
Ring Tension	17x17	63	10x10^{21}	20 - 120‡	298 - 673	.01 - 5
Nuclear Fuel Industry Research Program-III						
Burst	15x15	51	9x10^{21}	40 - 110‡	573 - 623	5x10^{-5}

‡ - Several samples were obtained from cladding with spalled oxide layers.

Robust Fuel Program

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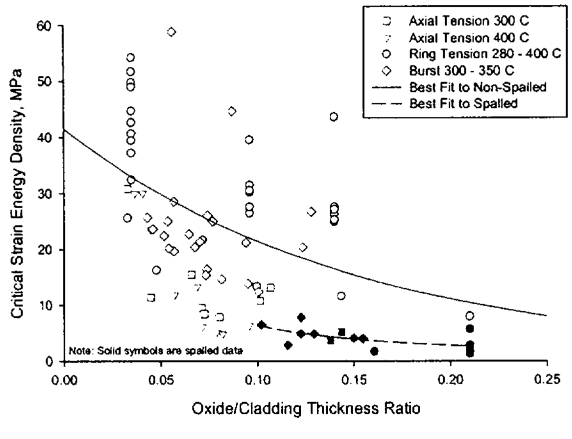
Cladding CSED Database

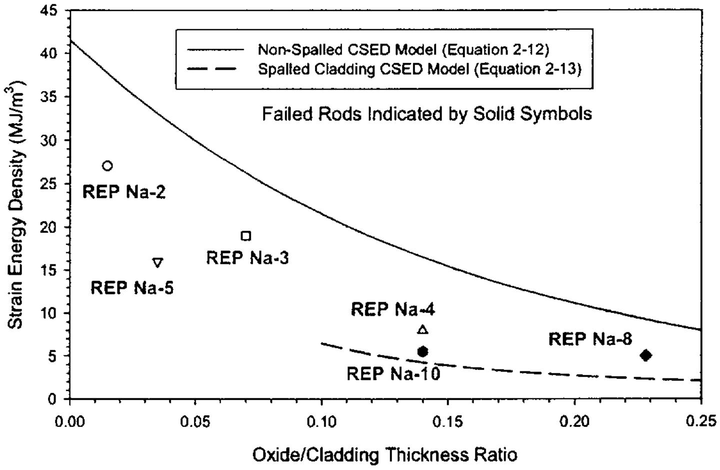


- Scatter is more related to test conditions and specimen design artifacts rather than to material variability
- Improved test designs will reduce the scatter
- Use of best-fit curves is justified when compared with failed-unfailed RIA database

Robust Fuel Program

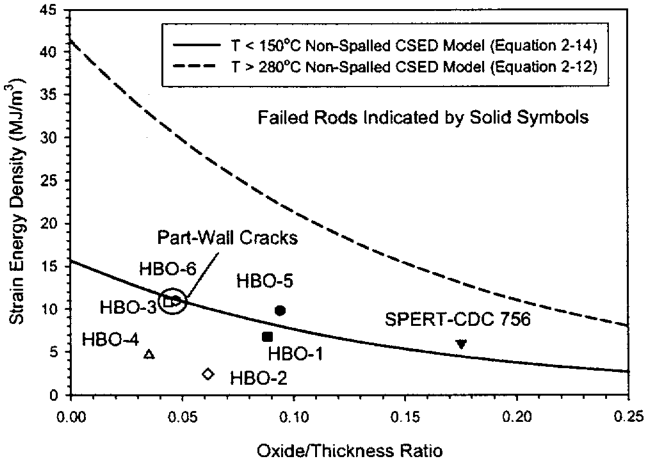
Analysis of High Burnup RIA-Simulation Tests

CABRI REP Na Tests on UO_2 Rods in Sodium Coolant



Analysis of High Burnup RIA-Simulation Tests

NSRR Tests on UO_2 Rods in Ambient Water



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Development of Fuel Rod Failure Threshold

- Construct Fuel Rod Failure Threshold Consistent with Current Licensing Approach
  - Fuel Enthalpy at Failure as a Function of Rod Average Burnup
  - Conservative Zircaloy-4 “Corrosion vs. Burnup” Correlation Used
    - » Relationship between cladding oxidation and rod average burnup

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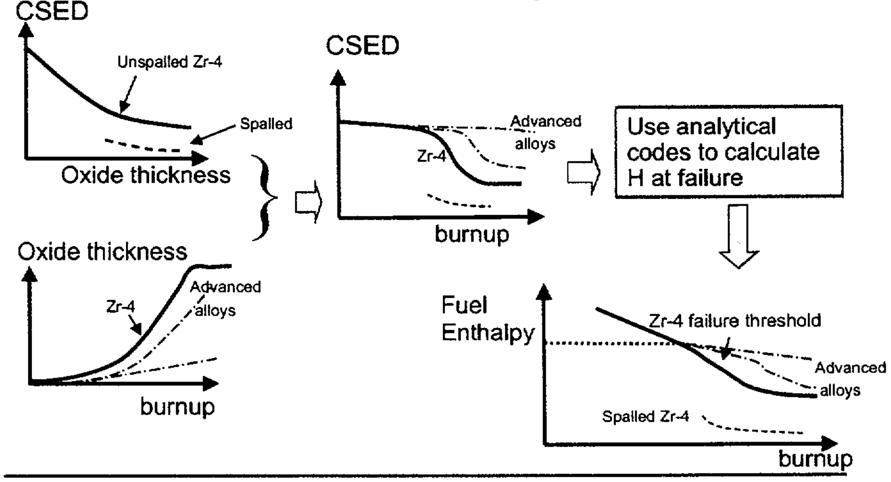
Approach to Develop Fuel Rod Failure Threshold

How to link clad ductility to burnup ?



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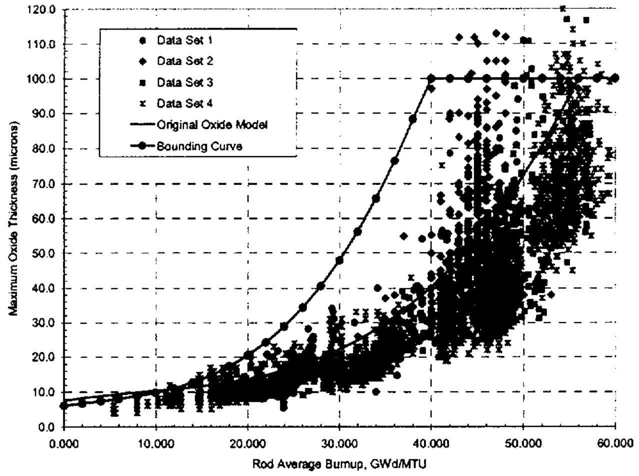
Maximum Oxide Thickness versus Burnup

Oxide Thickness Data for low-Sn Zr-4



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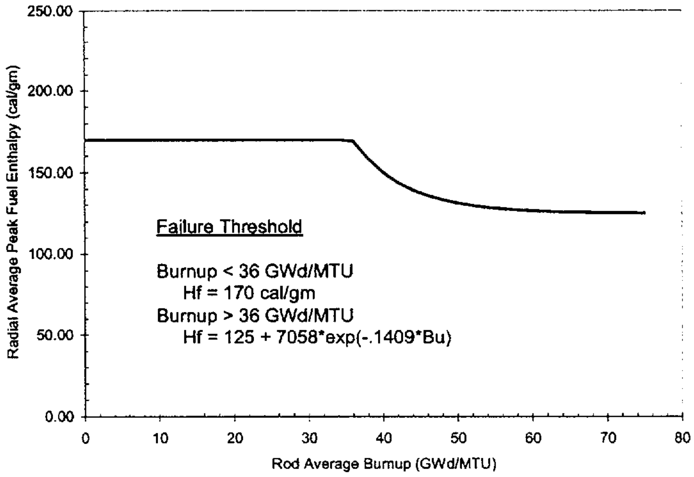
Revised Fuel Rod Failure Threshold

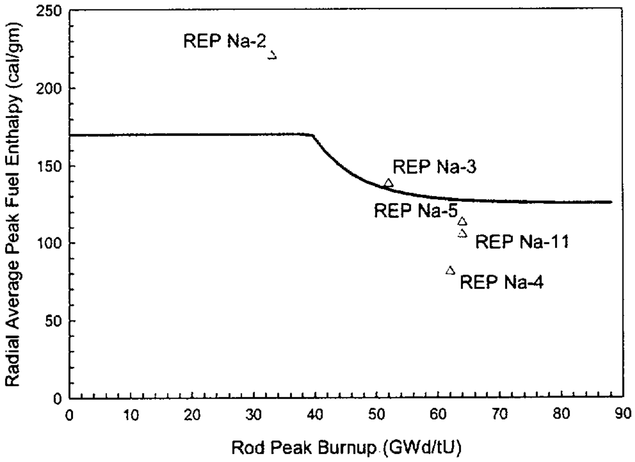


Failure Threshold

Burnup < 36 GWd/MTU
Hf = 170 cal/gm
Burnup > 36 GWd/MTU
Hf = 125 + 7058*exp(-.1409*Bu)

Failure Threshold Bounds CABRI Test Data With Non-Spalled Oxide Layers

(CABRI Tests in Sodium Coolant - 280°C)



Fuel Rod Behavior Leading to Core Coolability Concerns

- Experimental Database
  - Past experiments in US and Japan focused on fuel enthalpy above 280 cal/gm
    - » molten fuel dispersal kinetics
    - » Mechanical energy generation from fuel-coolant interaction
  - Recent experiments in France and Japan at fuel enthalpy levels below 220 cal/gm
    - » Some failures resulted in dispersal of a small amount of pellet material coming from the pellet periphery as finely fragmented solid particles
    - » Measurable mechanical energy generation

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Current understanding of fuel dispersal and related core coolability issues

- Fuel particle dispersal during power pulse following cladding failure
  - Potential may increase above 40 GWd/T due to rim formation in fuel pellets
  - Issues raised by fuel dispersal
    - » flow blockage and loss of rod geometry ?
    - » pressure pulse generation and threat on core geometry and pressure vessel integrity ?
- Data show that potential for fuel dispersal is a function of :
  - Energy deposition following cladding failure
  - Pulse width

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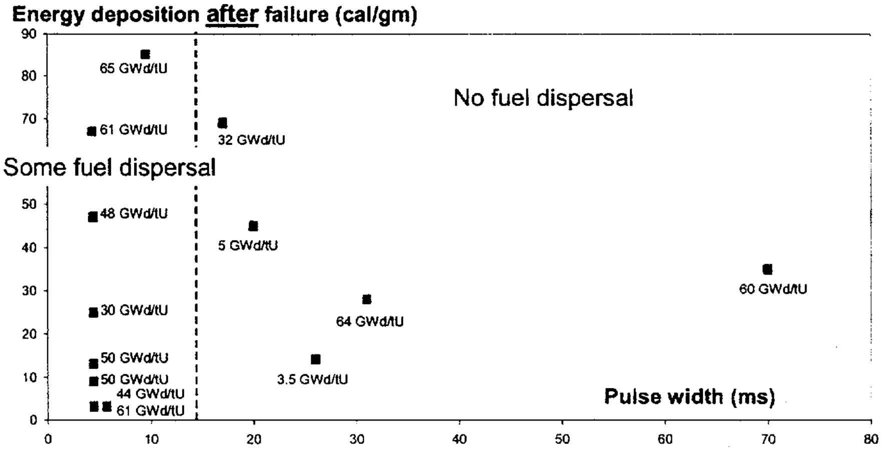
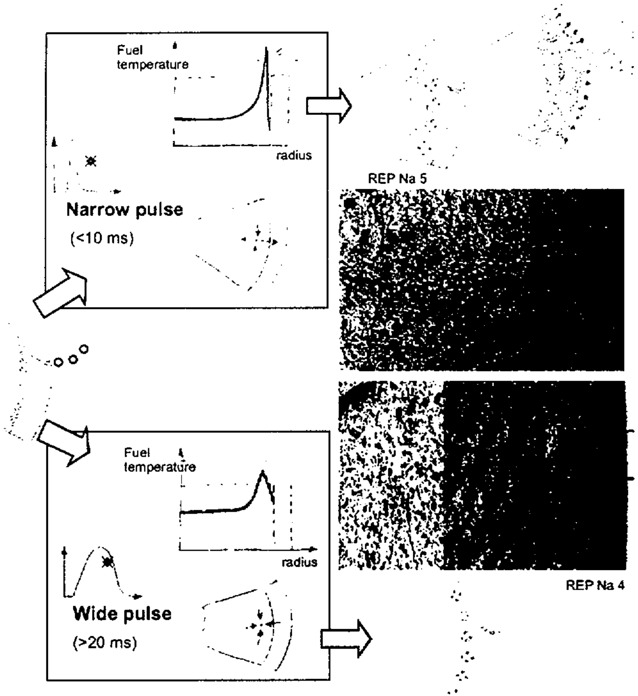
Pulse Width Effect on Fuel Dispersal



Note: Fuel dispersal observed **only** below 10 ms



Low heat transfer
- higher rim temperature
- steeper temperature gradient
  - higher gas pressure
  - higher thermal stresses
  - grain boundaries decohesion
  - gas release
  - **potential for fuel dispersal**

Higher heat transfer
- lower rim temperature
- smaller temperature gradient
  - lower gas pressure
  - lower thermal stresses
  - PCMI
  - limited gas release
  - **NO fuel dispersal after clad failure**

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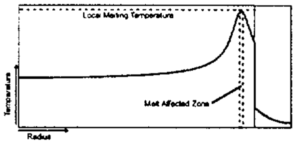
Post-Failure Behavior of High Burnup Fuel

- No fuel dispersal is expected for prototypical pulse widths
- At high energy after failure or narrow pulse, small amount of non-molten pellet material may be dispersed through failure opening but has low impact on:
  - Fuel rod geometry
    - » Experimental data (NSRR) show less then 10% of pellet material loss - mostly from rim region (1)
    - » Rod geometry is maintained in all cases (1)
  - Fuel-coolant interaction (leading to pressure pulses)
    - » Tests exhibited low mechanical energy conversion (1)
      - temperature of dispersed material lower than UO_2 melting
      - involved limited amount of material (from rim region only)

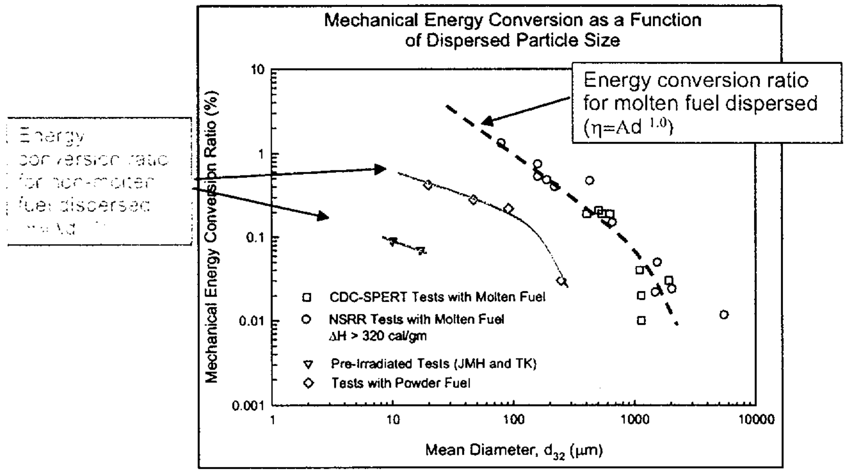
(1) T. Sugiyama and al. "Mechanical energy generation during high burnup fuel failure under RIA conditions". Journal of Nuclear Sciences and Technology, Vol 37, No. 10 October 2000

Basis for Coolability Limit

- Establish fuel enthalpy limit to preclude incipient melting of the pellet
- Data show dispersal of molten fuel produce higher thermal to mechanical energy conversion ratios
  - Incipient melting in JMH-5 Test at 210 cal/gm and 30 GWd/tU show no adverse impact on fuel rod geometry
  - Analysis shows no adverse impact on the pressure vessel integrity
- To use incipient fuel melting as a precursor for coolability limit is very conservative
  - Maintains clad temperatures below melting to ensure rod geometry
  - Small region of high burnup fuel near incipient melting due to radial temperature peaking
    - » Majority of fuel well below peak temperature
  - Limits thermal to mechanical energy conversion ratio



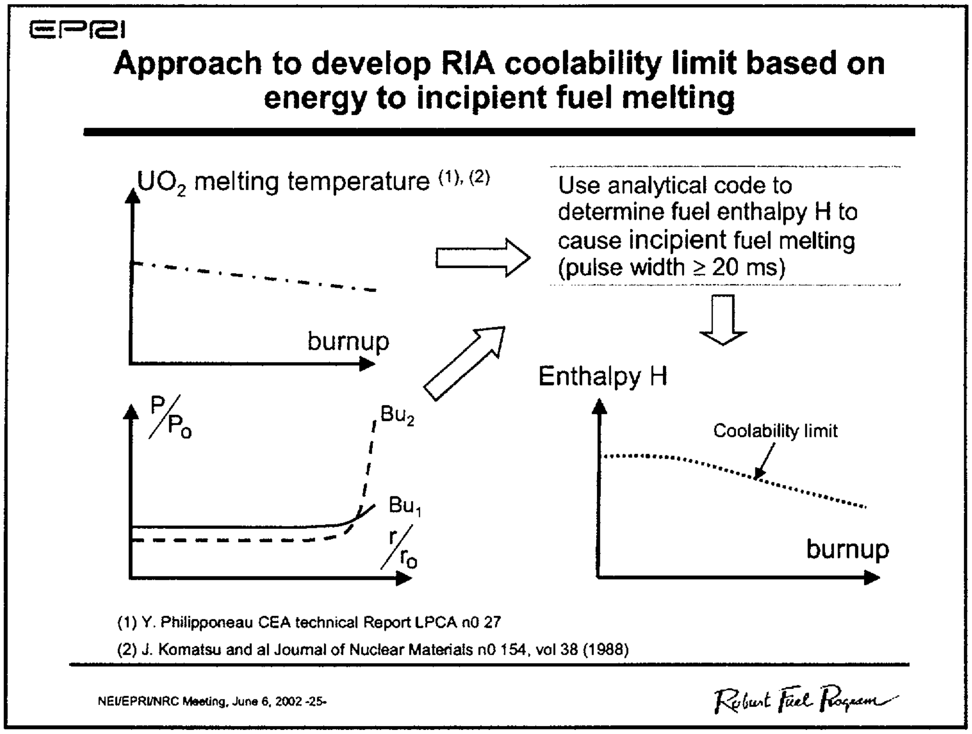
RIA Tests FCI Data



Energy conversion ratio for molten fuel dispersed ($\eta = Ad^{1.0}$)

Energy conversion ratio for non-molten fuel dispersed ($\eta = Ad$ [illegible])

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

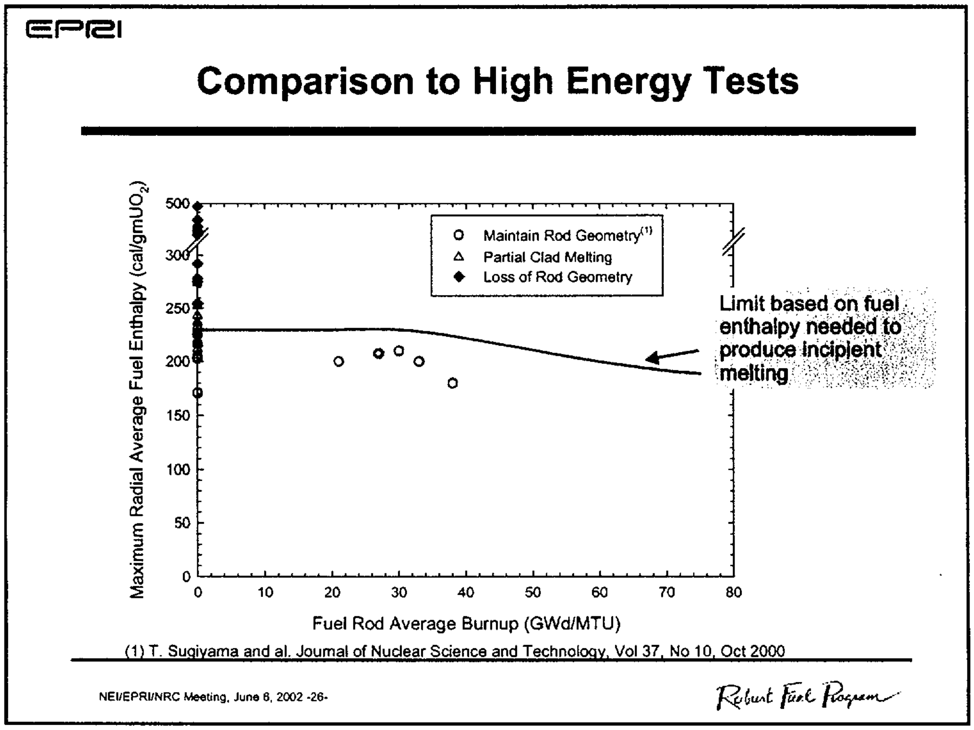


Approach to develop RIA coolability limit based on energy to incipient fuel melting

Use analytical code to determine fuel enthalpy H to cause incipient fuel melting (pulse width ≥ 20 ms)

(1) Y. Philipponeau CEA technical Report LPCA n0 27

(2) J. Komatsu and al Journal of Nuclear Materials n0 154, vol 38 (1988)

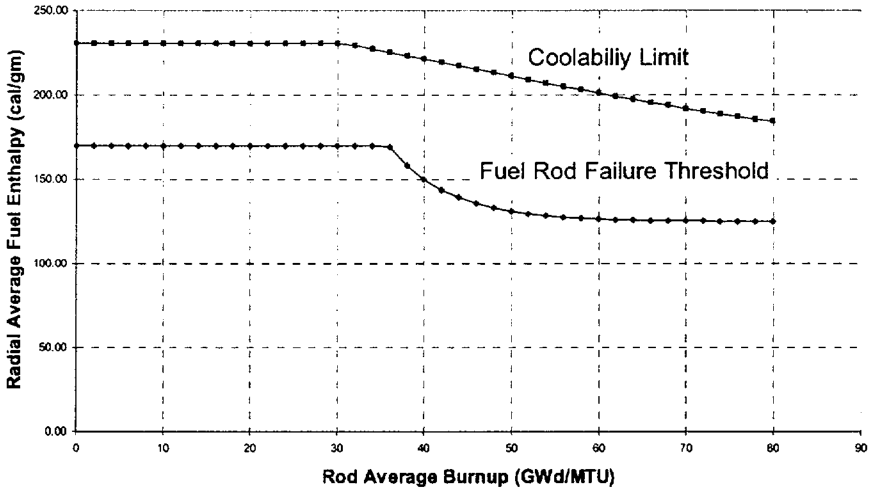


Comparison to High Energy Tests

Limit based on fuel enthalpy needed to produce incipient melting

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

Revised RIA Acceptance Criteria

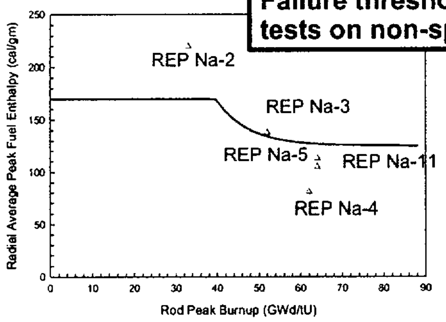


Summary (1)

- Revised clad failure threshold and core coolability limit as a function of burnup
  - Incorporates key controlling parameters
    - » Corrosion/hydriding evolution with burnup
    - » Burnup impact on UO_2 melting
- Criteria are given in terms of radial average peak fuel enthalpy
  - Applicable to HZP RIA
  - Use directly in core reload designs
  - Consistent with current practice
- DNB limit remains an acceptable criterion for at-power REA

Summary (2)

- Fuel Failure Threshold
  - Based on integral test results, mechanical property test data, and analytical approach
  - Represents a conservative lower bound for modern, low-corrosion cladding



Failure threshold bounds the data for tests on non-spalled Zr-4 rods

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Summary (3)

- Core Coolability Limit
  - No fuel dispersal expected under typical LWR conditions
  - However, fuel enthalpy limit established to minimize mechanical energy generation if fuel dispersal is assumed
    - » Limit peak fuel enthalpy to preclude incipient fuel melting
      - function of burnup
      - The limit is supported by data from both loss of rod geometry and mechanical energy release issues
    - » the limit is conservative
      - Small amount of fuel material involved (< 10%)
      - Large margin between burnup at peak power location during rod ejection and rod peak burnup used in UO_2 incipient melting calculation

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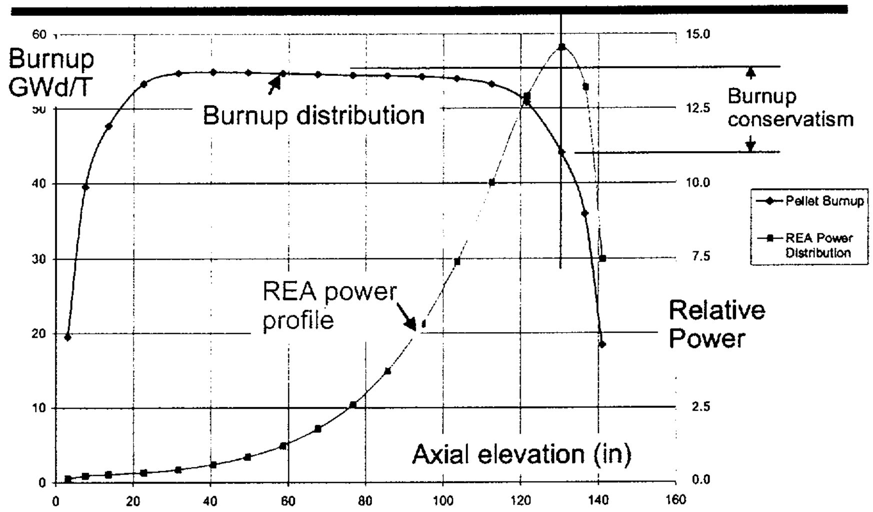
Conservatism

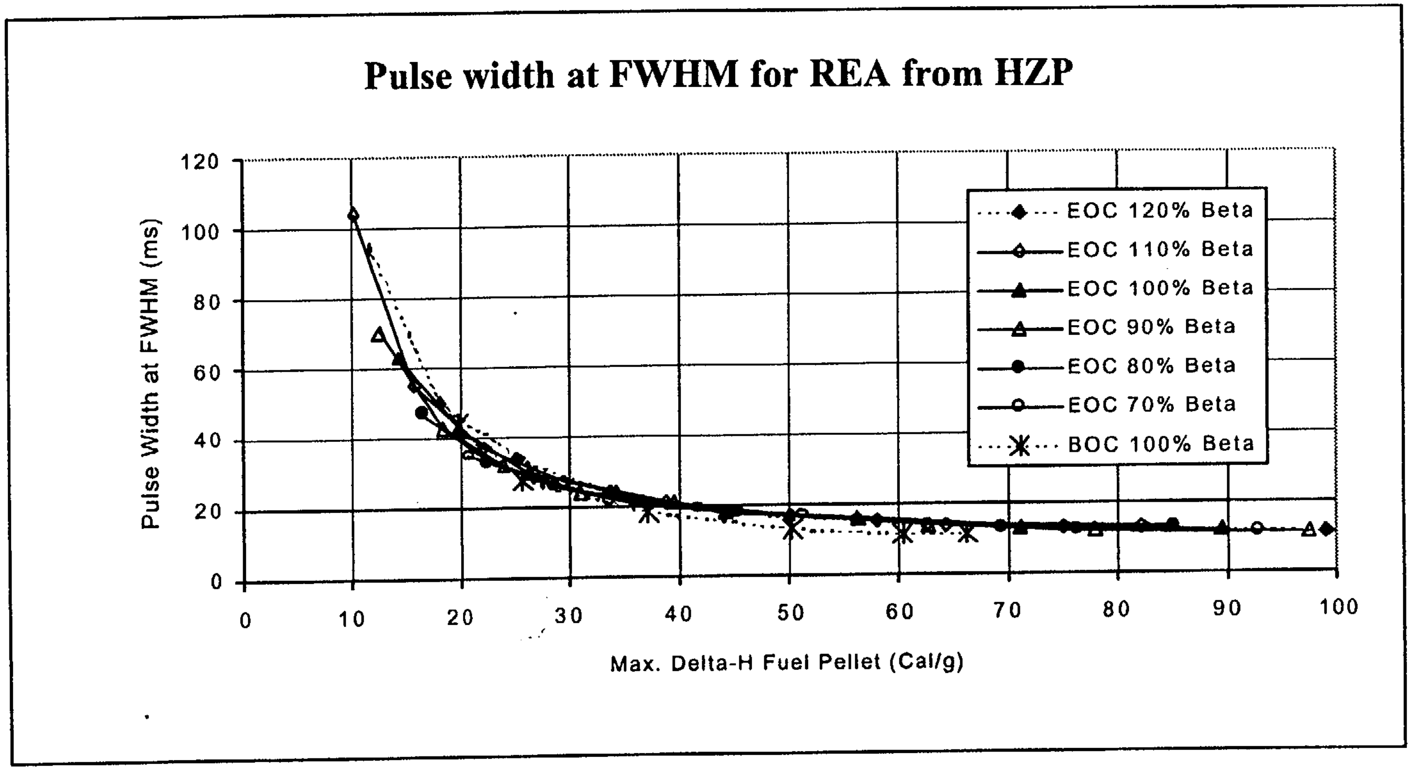


Fuel Dispersal NOT Possible For LWR Fuel

- NO fuel dispersal observed experimentally in RIA simulation tests with pulse widths > 20 ms
    - wide burnup range, 3-65 GWD/T
    - representative LWR pulse widths ~25-90 ms

- Fuel dispersal is not possible for LWR fuel at all burnup levels
    - supported by experimental data
    - lower rim temperature during the transients
    - lower thermal gradient in the rim
    - ~~lower~~ fuel fragmentation threshold
      higher

ATTACHMENT 3 SLIDE 1



Pulse width at FWHM for REA from HZP

ATTACHMENT 3 SLIDE 2