Cladding Hydrogen-Based Regulations in the United States

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Hydrogen-Based Regulations in the United States

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- Over 10 years of cladding transient-behavior research prompted a change in regulations to account for burnup effects
- Hydrogen identified as a major contributor to cladding mechanical behavior degradation with increasing burnup
- NRC revision of criteria for Loss-Of-Coolant Accident (LOCA) and Reactivity Initiated Accident (RIA) is in progress

New Proposed Hydrogen-Based LOCA Criterion

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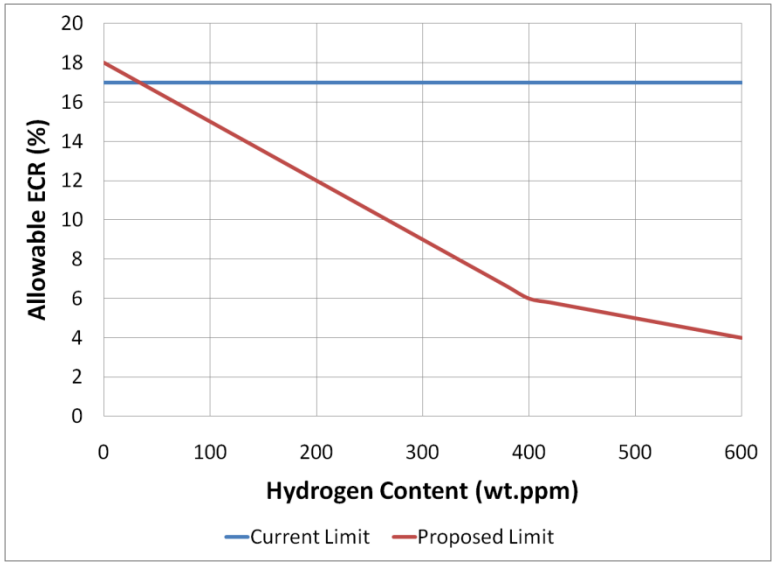
- New proposed LOCA criterion ensures residual ductility in non-ballooned sections of fuel rod
  - Ring Compression Test (RCT) at Argonne National Lab (ANL)



$$\begin{cases} ECR_{allowable} = 18 - 0.03 \times [H],\ 0 < [H] < 400\ wt.ppm \\ ECR_{allowable} = 10 - 0.01 \times [H],\ 400\ wt.ppm < [H] \end{cases}$$

- Allowable Equivalent Cladding Reacted (ECR) decreases as cladding hydrogen content [H] increases

- Update to 10 CFR 50.46 cladding embrittlement criteria

New Proposed Hydrogen-Based RIA Criterion

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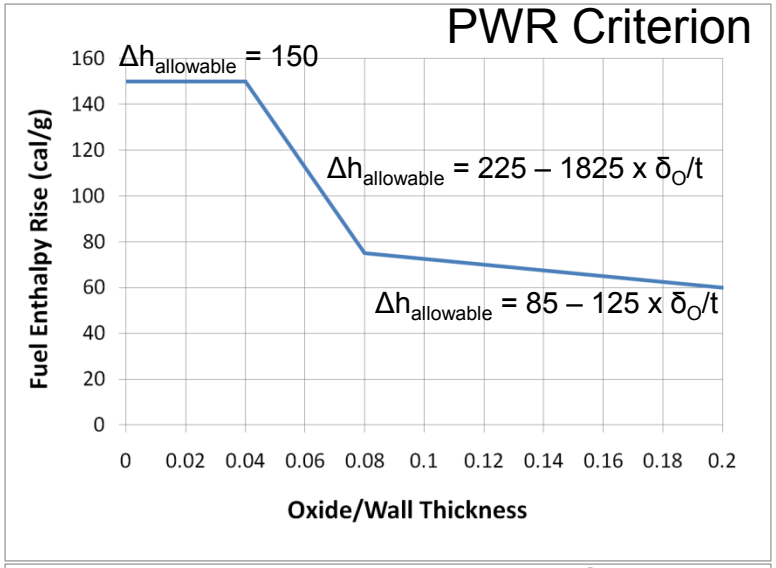
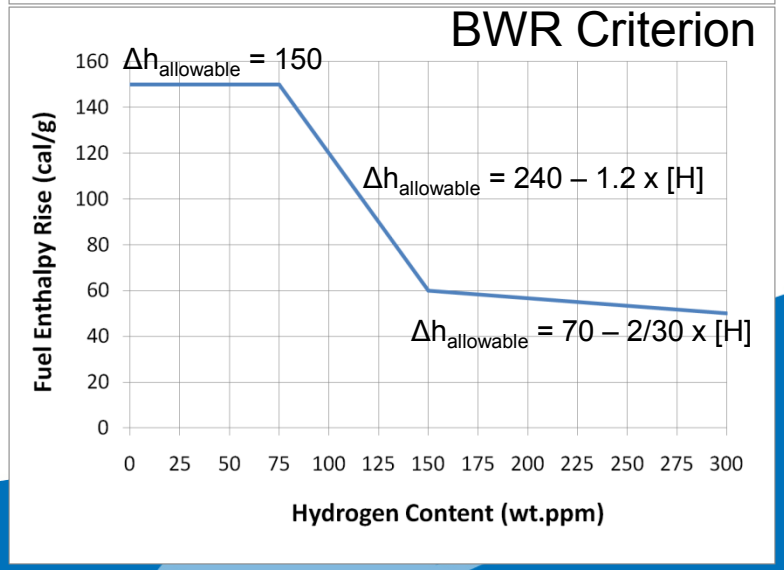
- New draft criterion takes into account effects of oxidation and hydriding on fuel enthalpy rise (Δh) to failure
  - In-pile RIA testing: France (CABRI), Japan (NSRR), Kazakhstan (IGR), Russia (BIGR), and the United States (PBF, TREAT)
- PWR criterion can be plotted against [H] for various alloys if the alloy's hydrogen pickup fraction is known
- Update to NUREG-0800: Standard Review Plan, Ch. 4.2 Appendix B





Objectives of this Study

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- Obtain hydrogen content [H] as a function of rod burnup BU to investigate burnup dependence of LOCA and RIA criteria
  - Use FRAPCON-3.4 to predict [H] vs. BU for U.S. cladding alloys
    - Constant alloy-dependent hydrogen pickup fractions
    - Zircaloy-2: BU dependent oxidation model: direct [H] vs. BU relationship
    - Zircaloy-4, ZIRLO™, M5™: heat flux, neutron flux, temperature, and time dependent model: complex indirect [H] vs. BU relationship

- Generate BU dependent allowable ECR and Δh for U.S. cladding alloys for different core axial elevations and power histories
  - Compare BU dependent LOCA and RIA limits as a function of cladding alloy

FRAPCON-3.4 Fuel Performance Modeling

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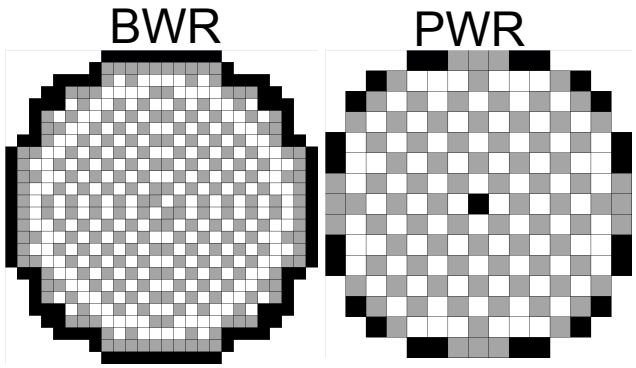
- Typical GE BWR/4
  - 10x10 fuel assembly, Zircaloy-2 cladding
- Typical Westinghouse 4-loop PWR
  - 17x17 fuel assembly, ZIRLO™ cladding
- Core-load patterns and rod average power from plant safety analysis reports
- Best guess at representative power histories for 2-cycle and 3-cycle lifetimes
  - 7 PWR and 18 BWR power histories
- PWR histories based on ZIRLO™ cladding used for Zircaloy-4 and M5™



BWR

Core average LHGR (kW/m)				16.0
Cycle	Power	Rod Average LHGR (kW/m)		
		BOC	MOC	EOC
1	High	20.5	17.8	21.2
	Mid	17.2	15.7	18.5
	Low	16.4	14.3	16.9
2	High	17.4	16.0	17.9
	Mid-High	17.4	14.5	15.4
	Mid-Low	15.2	12.7	13.4
	Low	13.1	10.6	11.0
3	High	12.9	9.8	10.5
	Mid-High	10.1	9.0	7.4
	Mid-Low	8.9	7.0	6.9
	Low	7.6	5.9	5.7

PWR

Core average LHGR (kW/m)				19.0
Cycle	Power	Rod Average LHGR (kW/m)		
		BOC	MOC	EOC
1	High	25.5	25.7	24.2
	Mid	23.6	24.8	23.7
	Low	19.5	18.7	19.9
2	High	22.8	23.9	23.2
	Mid-High	21.9	20.5	20.8
	Mid-Low	19.9	19.8	19.2
	Low	11.1	11.1	12.2
3	Mid	19.4	19.5	19.0
	Low	10.1	9.8	11.1

FRAPCON-3.4 Hydrogen Models

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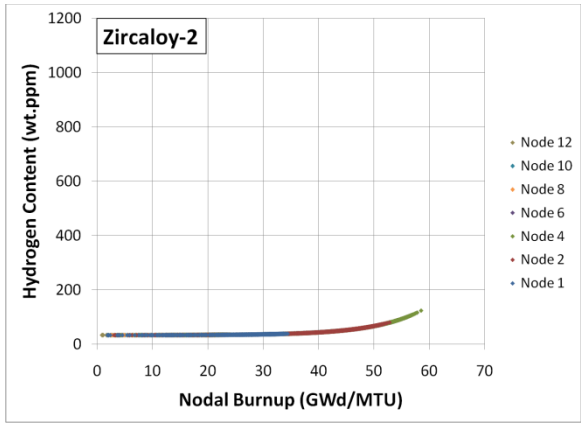
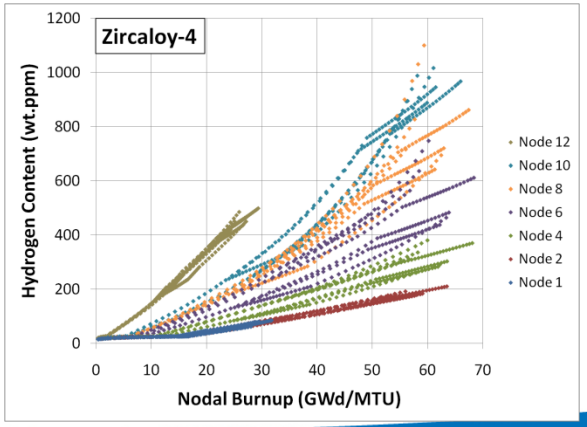
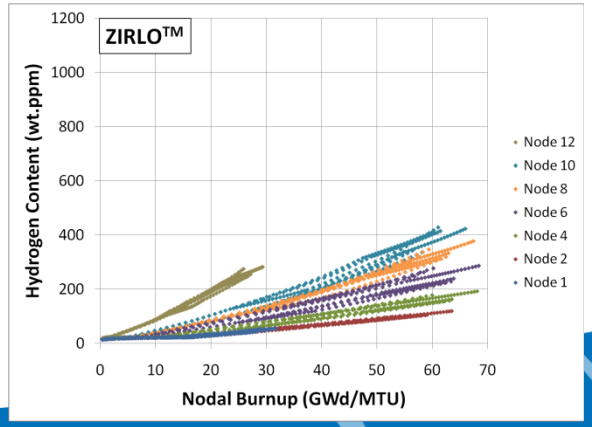
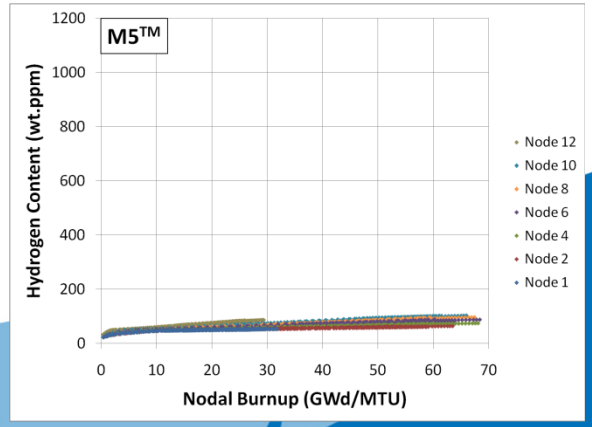
- Zircaloy-2 [H] only dependent on BU: no axial-node dependence
- PWR alloys: strong temperature and heat flux dependence
  - Zircaloy-4: high oxidation and H pickup fraction
    - Early transition in oxidation kinetics (δ_{oxide}>2µm)
    - Oxidation beyond allowable limits
  - ZIRLO™: intermediate behavior
  - M5™: low oxidation and H pickup fraction









Burnup-Dependent Allowable ECR During a LOCA

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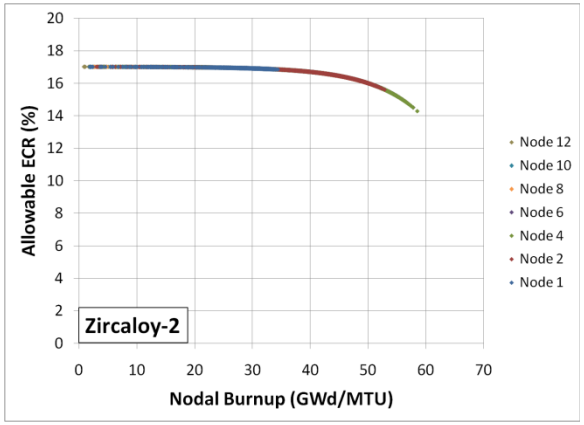
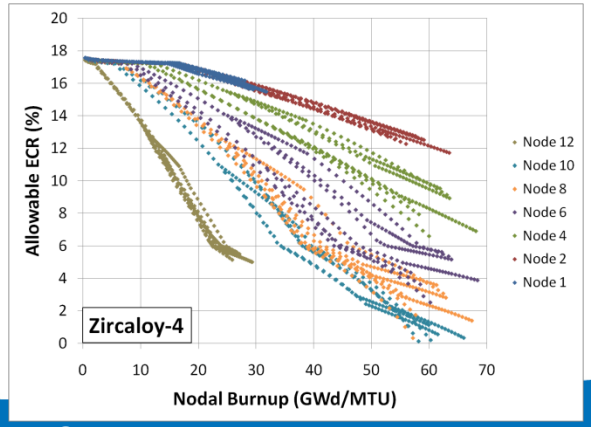
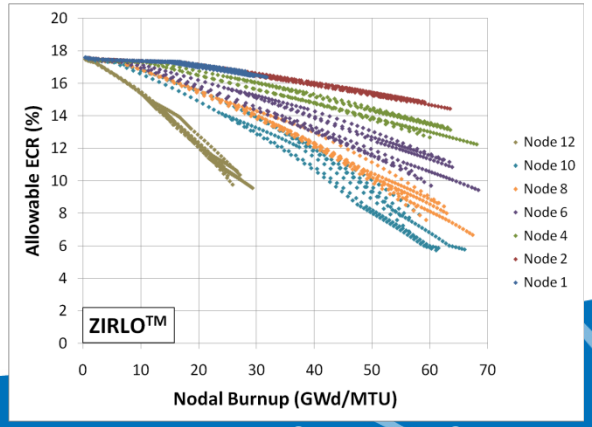
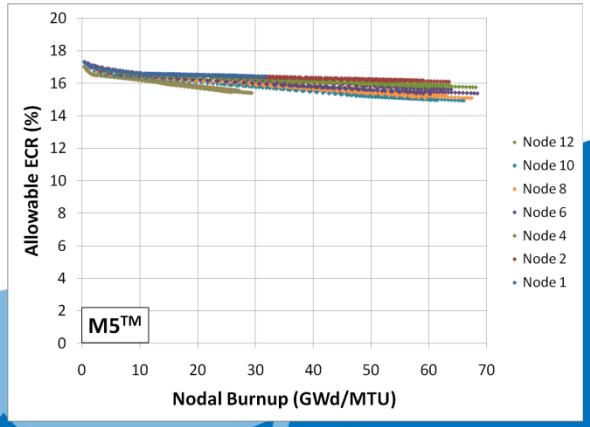
- [H] vs. BU relationships used as input for LOCA criterion (NOT a LOCA analysis)
  - BU dependent curves produced for each alloy, power history, and axial node
- BWR - Zircaloy-2: no predicted axial node and power history variations
  - High allowable ECR below 50 GWd/MTU
  - Rapid degradation above 60 GWd/MTU
- PWR: large axial node and power history variations
  - Zircaloy-4 shows largest variations:
    - 5% ECR for a given axial node due to power history
    - 12% ECR variation between top and bottom of core
  - M5™ least predicted variation (slow oxidation kinetics)









Allowable ECR During a LOCA Alloy Model Comparison

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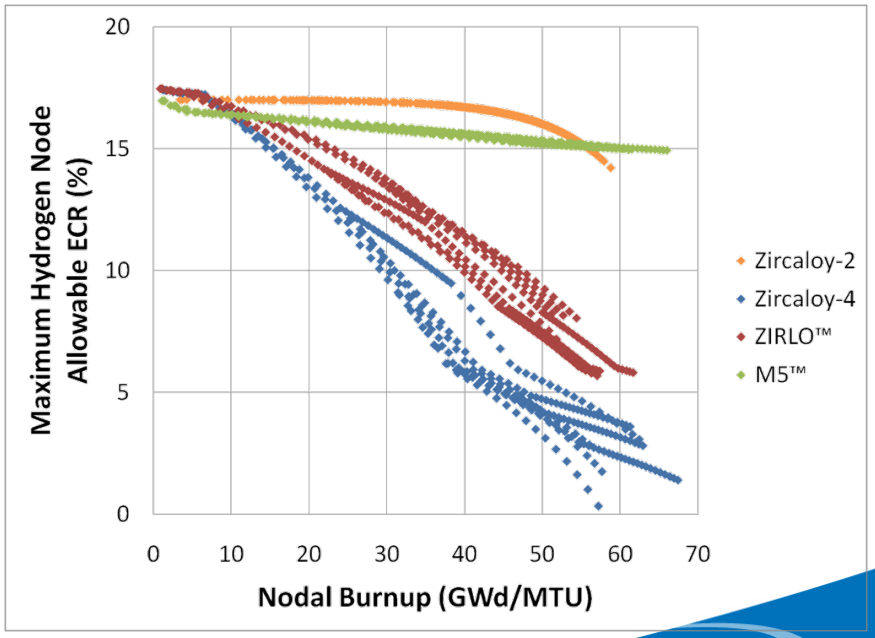
- Zircaloy-2 in BWR
  - Better predicted performance than PWR alloys in PWR environment
  - Rapid degradation at high burnup: 0% $ECR_{allowable}$ predicted at 79 GWd/MTU

- PWR alloys:
  - Highest H pickup for Zircaloy-4
    - Lowest margin for Zircaloy-4
  - Zircaloy-4 plants more challenged by new criterion than M5™ and ZIRLO™ plants

Note: ZIRLO™ power histories used for Zircaloy-4 and M5™



Burnup-Dependent Allowable Δh_{fuel} During a RIA

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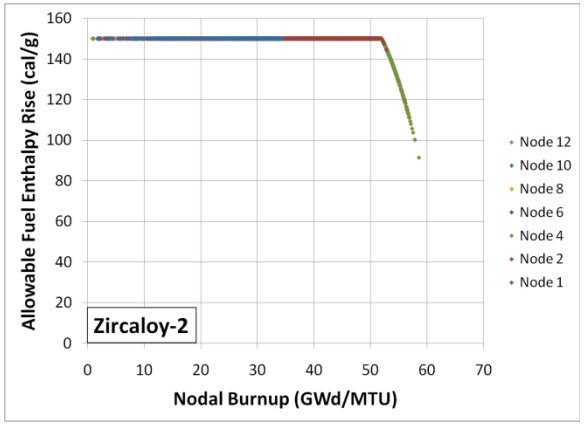
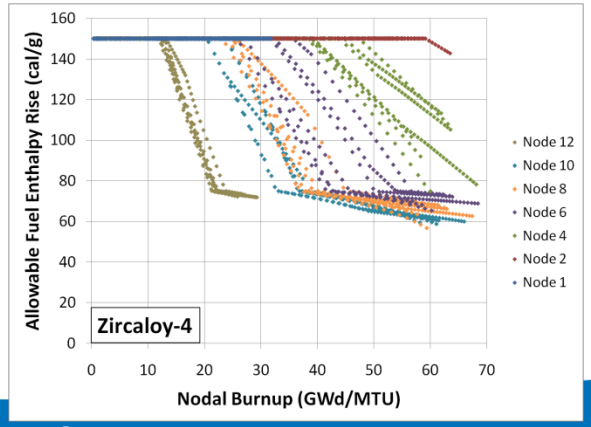
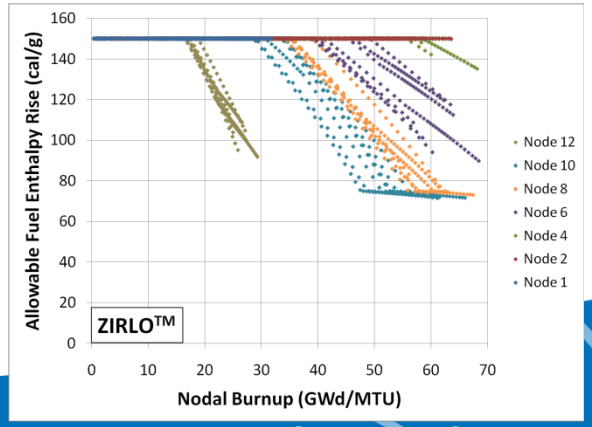
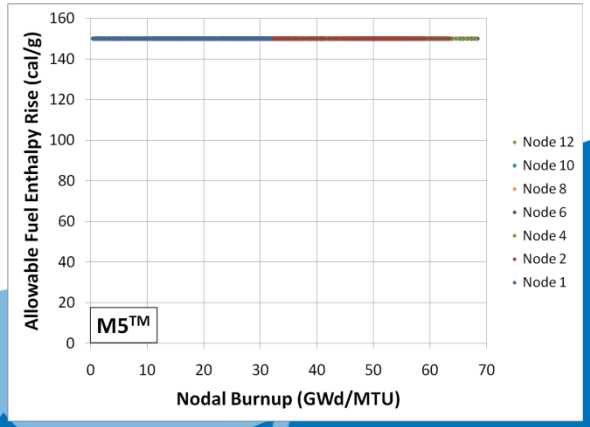
- [H] vs. BU and δ_{oxide} vs. BU relationships used as input for RIA criterion
  - BU dependent curves produced for each alloy, power history, and axial node
- BWR - Zircaloy-2: no predicted axial node and power history variations
  - No degradation in allowable Δh_{fuel} below 52 GWd/MTU
  - Rapid degradation above 52 GWd/MTU
- PWR: large axial node and power history variations
  - Zircaloy-4 shows largest variations:
    - 60 cal/g for a given axial node due to power history
    - 80 cal/g variation between top and bottom of core
  - M5™ very slow oxidation kinetics: no predicted degradation









Allowable Δh_{fuel} During a RIA Alloy Model Comparison

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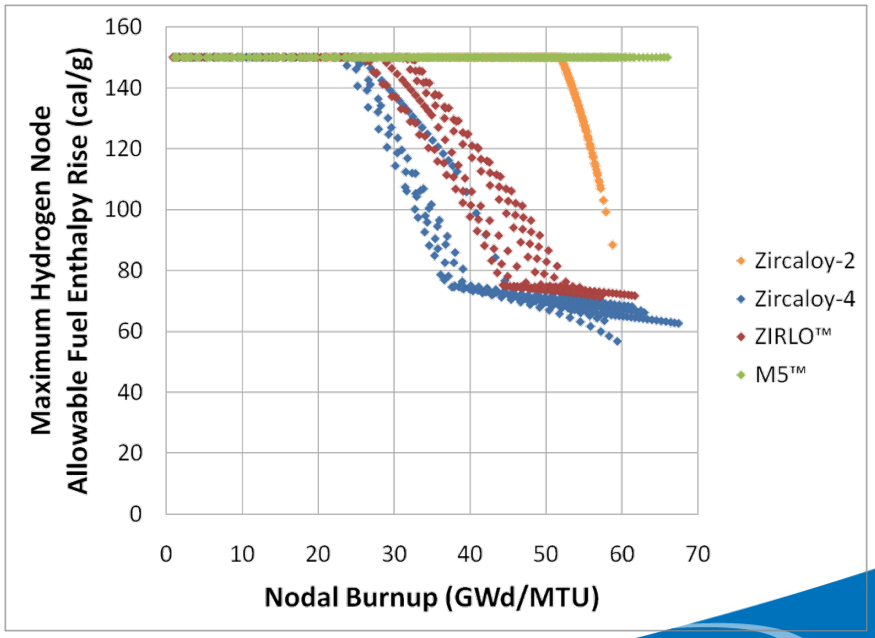
- Zircaloy-2 in BWR
  - Better predicted performance than Zircaloy-4 and ZIRLO™ in PWR
  - Rapid degradation at high burnup: $\Delta h_{allowable}$=0 predicted at 80 GWd/MTU

- PWR alloys:
  - Earlier degradation for Zircaloy-4 than ZIRLO™ (~10 GWd/MTU)
  - No predicted degradation for M5™
  - Zircaloy-4 and ZIRLO™ plants more challenged by new criterion than M5™ plants

Note: ZIRLO™ power histories used for Zircaloy-4 and M5™



Summary and Conclusions (1/2)

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- The analytical relationship between burnup and cladding degradation (oxidation and hydrogen) was investigated for a typical BWR (BWR/4) and PWR (W 4-loop) of the U.S. fleet
  - For Zircaloy-2 in a BWR environment, the FRAPCON-3.4 models for hydrogen pickup are entirely dependent on burnup
  - For Zircaloy-4, ZIRLO™, and M5™ in a PWR environment, the relationship between hydrogen and burnup is dependent on power history and axial position in the core
  - For PWR environments, the axial position in the core has a larger impact than the power history of the rod on predicted hydrogen content as a function of burnup

Summary and Conclusions (2/2)

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- Burnup dependent ECR and fuel enthalpy rise were generated for Zircaloy-2, Zircaloy-4, ZIRLO™, and M5™ for the proposed LOCA and RIA criteria to be implemented in the near future
  - For identical power histories, PWRs using Zircaloy-4 will be challenged earlier than plants using more modern alloys such as ZIRLO™ or M5™
  - Within the assumptions of this study, and based on FRAPCON-3.4 predictions, Zircaloy-2 behaved well compared to the PWR alloys until a certain burnup level was reached, typically 50-55 GWd/MTU
  - At high burnup, the predicted performance of Zircaloy-2 in BWRs would be worse than for ZIRLO™ and M5™ in PWRs, and the predicted limits would become equal to zero around 79-80 GWd/MTU

Q & A

Please send questions to

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