ELECTRIC POWER RESEARCH INSTITUTE

Industry Technical Input on the RIA Failure Threshold

NRC – Industry Workshop RIA Criteria

September 25, 2008

Washington, DC

Prior Public Workshops on RIA Acceptance Criteria

- 1st and 2nd workshops prior to issuance of NUREG-0800 Rev.3 with interim criteria in Appendix B
  - Industry provided input on the technical bases of the criteria, e.g. hydrogen effect, failure modes, definition of terms, etc.
  - Appreciate the opportunity to provide input into the development of the interim criteria for new reactors
- 3rd workshop focused on approach to reach final criteria
  - Technical conservatisms with experimental data from test reactors used to develop interim cladding failure threshold
  - Approach to demonstrate develop coolability limit that addresses cladding failure of irradiated fuel

© 2006 Electric Power Research Institute, Inc. All rights reserved.

Industry Presentations in the 4th Workshop on RIA Acceptance Criteria

- Expected adjustments to experimental data used to develop failure threshold
- Options to develop enthalpy limits to meet the coolability criteria
- Industry comments on implementation issues

© 2006 Electric Power Research Institute, Inc. All rights reserved.

Failure Threshold Development

- Industry methodology to adjust experimental data
  - PWR PCMI Failure Criteria
    - Temperature Scaling of NSRR tests
    - MOX effects
  - BWR PCMI Failure Criteria
    - Pulse width effects for BWRs
- Hydrogen Accumulation Models
- Summary

© 2006 Electric Power Research Institute, Inc. All rights reserved.

Conservatisms in PCMI Failure Criteria

- NSRR RIA tests at room temperature (CZP) over emphasizes role of corrosion/hydrogen on clad ductility
  - Anticipate that tests in the high temperature (~290ºC) capsule in NSRR will allow improved scaling of NSRR room temp. tests
- Data/models show that irradiated MOX pellet expands more than UO_2 at same enthalpy level
  - Pellet expansion effects can be evaluated to adjust for UO_2 limits
- Low failure enthalpy for BWR NSRR tests driven by 20ºC temperature and narrow pulse width conditions
  - Wider pulse widths increase temperature and ductility
  - Hydrogen solubility increase with temperature improves cladding ductility

© 2006 Electric Power Research Institute, Inc. All rights reserved.

Method to Evaluate and Scale RIA Experiments

- Adjustment factors (or scaling) required to apply results from non-prototypical experiments to LWR RIA hypothetical accidents
  - Requires analytical methods qualified with experimental data
  - Use sensitivity studies to evaluate impact of changes in initial temperature, pellet material, and pulse characteristic
- NRC and Industry have developed different magnitudes for factors to adjust RIA test data
  - Work on-going to clarify the cause of the differences between scaling factors determined with FRAPTRAN and FALCON
  - Move to a consistent method to calculate adjustment for the RIA data

© 2006 Electric Power Research Institute, Inc. All rights reserved.

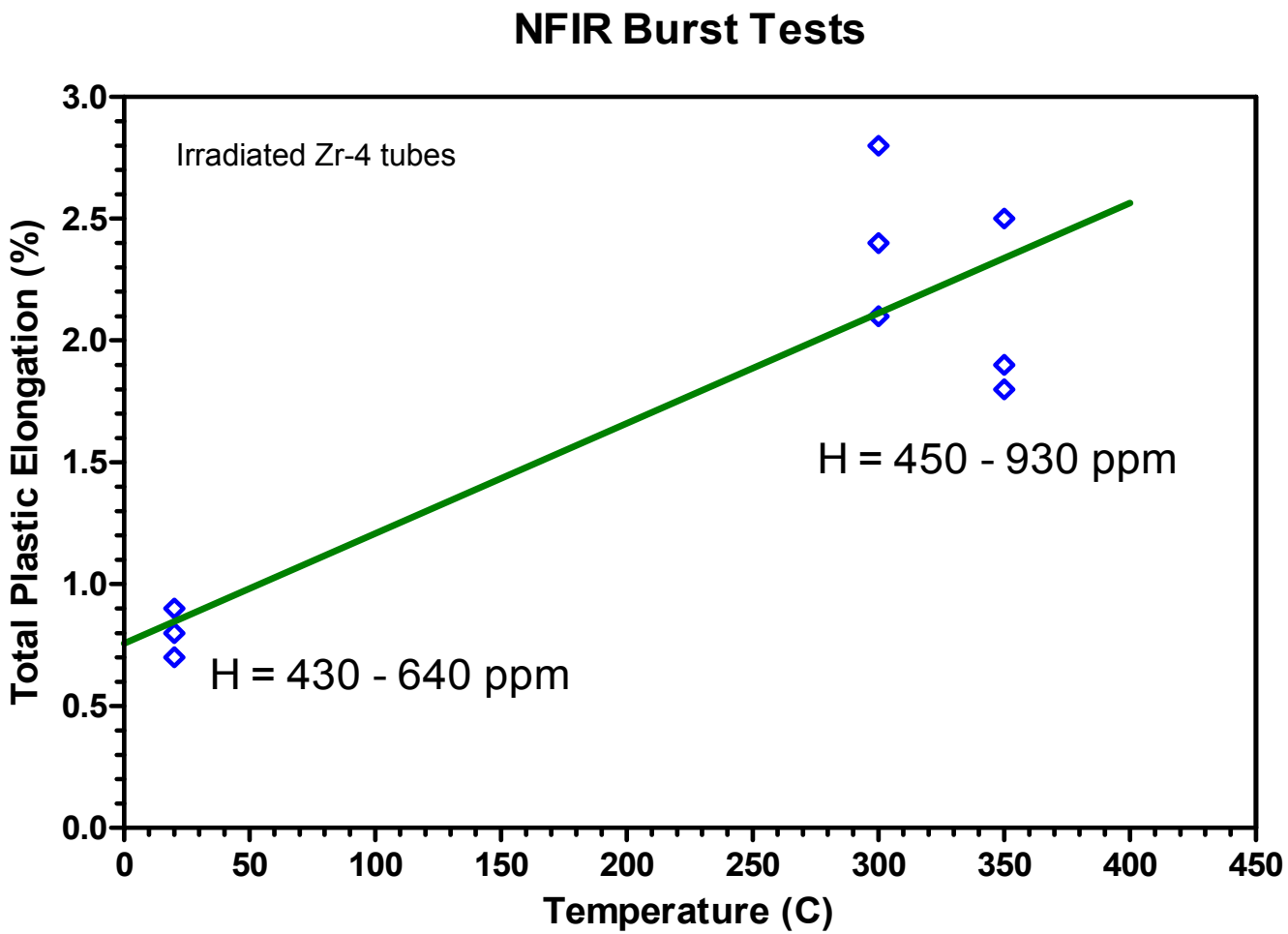
Action Plan to Adjust Room Temperature NSRR Tests

- Confirm high temperature clad failure model using high temperature tests in NSRR
  - May require detailed modeling to account for small rodlet geometry end effects
  - Results expected in Spring 2009

- Use failure model for high temperature conditions to calculate increase in failure enthalpy for 20ºC NSRR PWR tests
  - Develop ΔH adjustment as function of hydrogen content to be added to NSRR test results

© 2006 Electric Power Research Institute, Inc. All rights reserved.

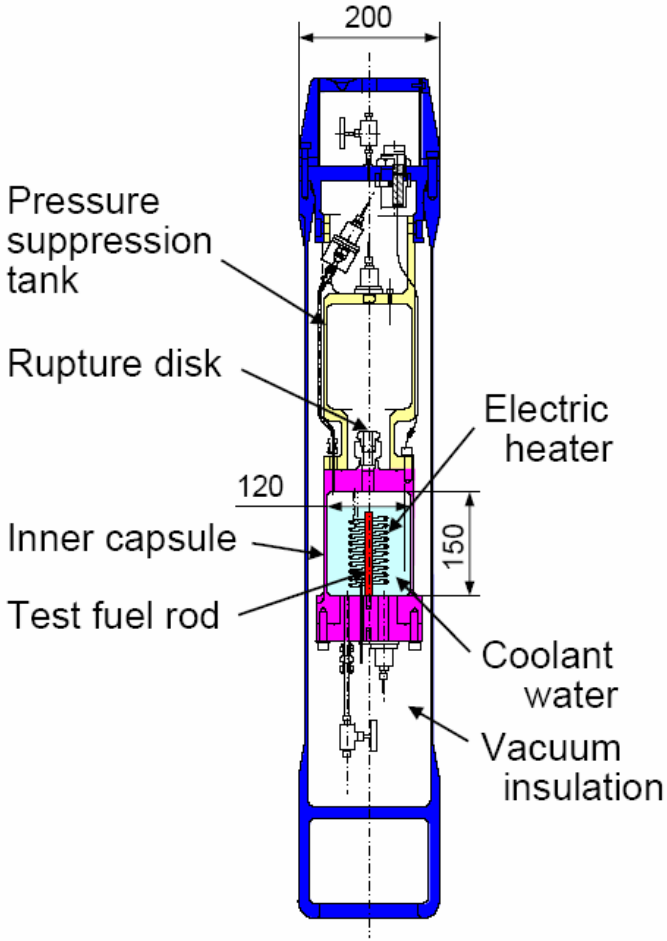
Temperature Effect on Ductility of Hydrided Cladding



© 2006 Electric Power Research Institute, Inc. All rights reserved.

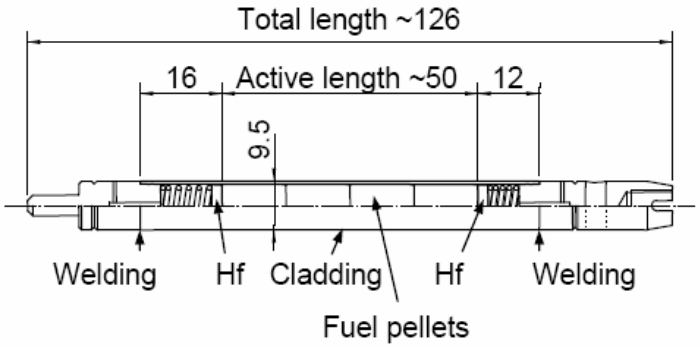
ELECTRIC POWER RESEARCH INSTITUTE

High Temperature / High Pressure Test Capsule



High temperature test capsule

Test fuel rod
- Total length ~126 mm
- Active length ~50 mm



Coolant water
- Stagnant
- up to 286 deg C, 7 MPa

Instrumentation
- Cladding surface thermocouple
- Coolant thermocouple
- Capsule pressure sensors

© 2006 Electric Power Research Institute, Inc. All rights reserved.

Planned High Temperature Tests in NSRR

Fuel Type, Cladding, Burnup	Room Temperature Tests*	High Temperature tests **	Corrosion/Hydrogen
PWR-UO_2, ZIRLO, 71 GWd/t	VA-1	VA-3, May 08	~70 µm / 760 ppm
PWR-UO_2 , MDA, 77 GWd/t	VA-2	VA-4, Nov. 08	~70 µm / 660 ppm
BWR-UO_2 , Zry-2, 69 GWd/t	LS-1	LS-2, Jun. 08	~25 µm / 300 ppm
PWR-MOX, Zry-4, 59 GWd/t	BZ-2	BZ-3 late 07	~20 µm / 150 ppm

* The 4 RT tests resulted in PCMI Failure

** Corresponding RT and HTHP Test fuel rods were sampled from an identical fuel segment

Room temperature tests completed prior to 2008

© 2006 Electric Power Research Institute, Inc. All rights reserved.

Adjust MOX Effect on Pellet Expansion

- Interim failure criteria based on lower bound of adjusted RIA-simulation tests that includes MOX fuel
  - Adjustments were made assuming no difference exists between UO_2 and MOX fuel pellet response
  - More severe loading response in irradiated MOX fuel pellet due to widely distributed high burnup structure throughout pellet
- Recent results from MOX tests on BWR and PWR rods from NSRR
  - Burnups range from 45 to 59 GWd/tU
  - Tested in room temperature capsule
  - Lower burnup BWR rod survived, two high burnup PWR rods failed – Pu agglomerate or Temp. effect ?

© 2006 Electric Power Research Institute, Inc. All rights reserved.

Actions to Adjust REP Na-7 MOX Test

- Validating FALCON MOX model using both NSRR and CABRI MOX tests
  - Pellet expansion effects as function of MOX pellet type, temperature, and burnup
  - Compare analysis with results (cladding deformation and failure status) from failed and non-failed MOX tests

- Use FALCON to calculate enthalpy at failure for CABRI REP Na-7 assuming irradiated UO_2 pellets
  - Develop ΔH adjustment to be added to MOX test results
  - Preliminary assessments find ΔH adjustment ~80 cal/gm

© 2006 Electric Power Research Institute, Inc. All rights reserved.

BWR-Specific Issues in Control Rod Drop Accident

- Accident can initiate at temperatures well below 280ºC
  - Ranges from room temperature to 250 C
- Power pulse shapes significantly non-gaussian, especially at low temperature with large fraction of non-prompt energy deposition
  - Slower energy deposition rates allows for heat conduction to the cladding
- Scaling of experimental data is required to develop final failure threshold to account for heat conduction effects
  - Increase of failure enthalpy due to ductility improvements

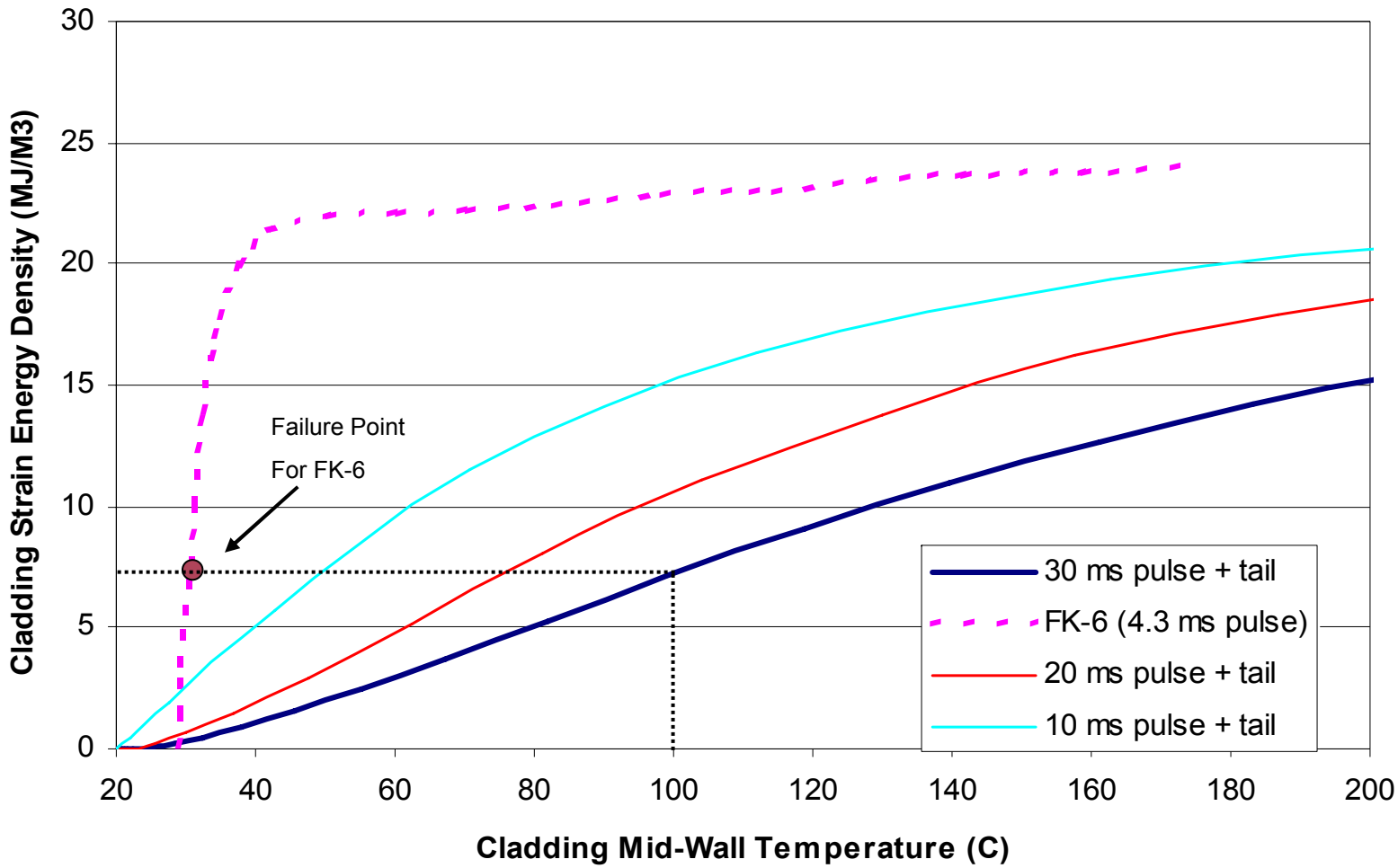
© 2006 Electric Power Research Institute, Inc. All rights reserved.

BWR PCMI Interim Failure Criterion

- Interim failure criterion uses lower bound of BWR NSRR tests
  - Rapid energy deposition leads to clad loading at low temperature
  - Results in low failure enthalpy (~60 cal/gm)
- Increase in cladding temperature and improvement of cladding ductility during energy deposition of BWR CRDA
  - Influence of the pulse width differences (4 ms versus 30 ms) between experiments and postulated rod drop accident
- Awaiting results of high temperature test in NSRR (LS-2)
  - Use to qualify the analysis method to scale the other BWR RIA tests in NSRR

© 2006 Electric Power Research Institute, Inc. All rights reserved.

FALCON Calculated Strain Energy Density as a Function of Cladding Mid-Wall Temperature

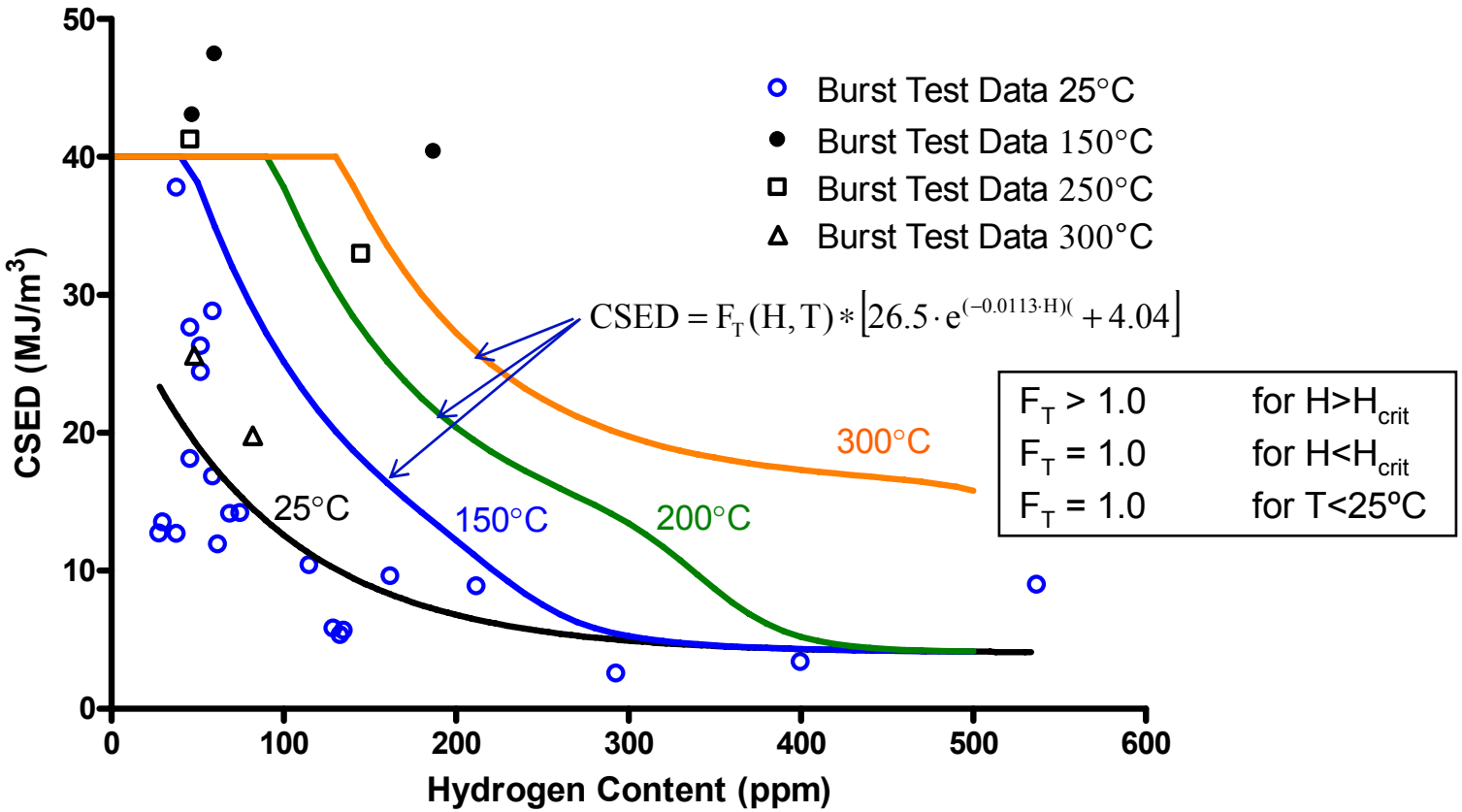


© 2006 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Temperature Dependent CSED Model for BWRs

Rapid Burst Tests - (NFIR-IV and TEPCO)



© 2006 Electric Power Research Institute, Inc. All rights reserved.

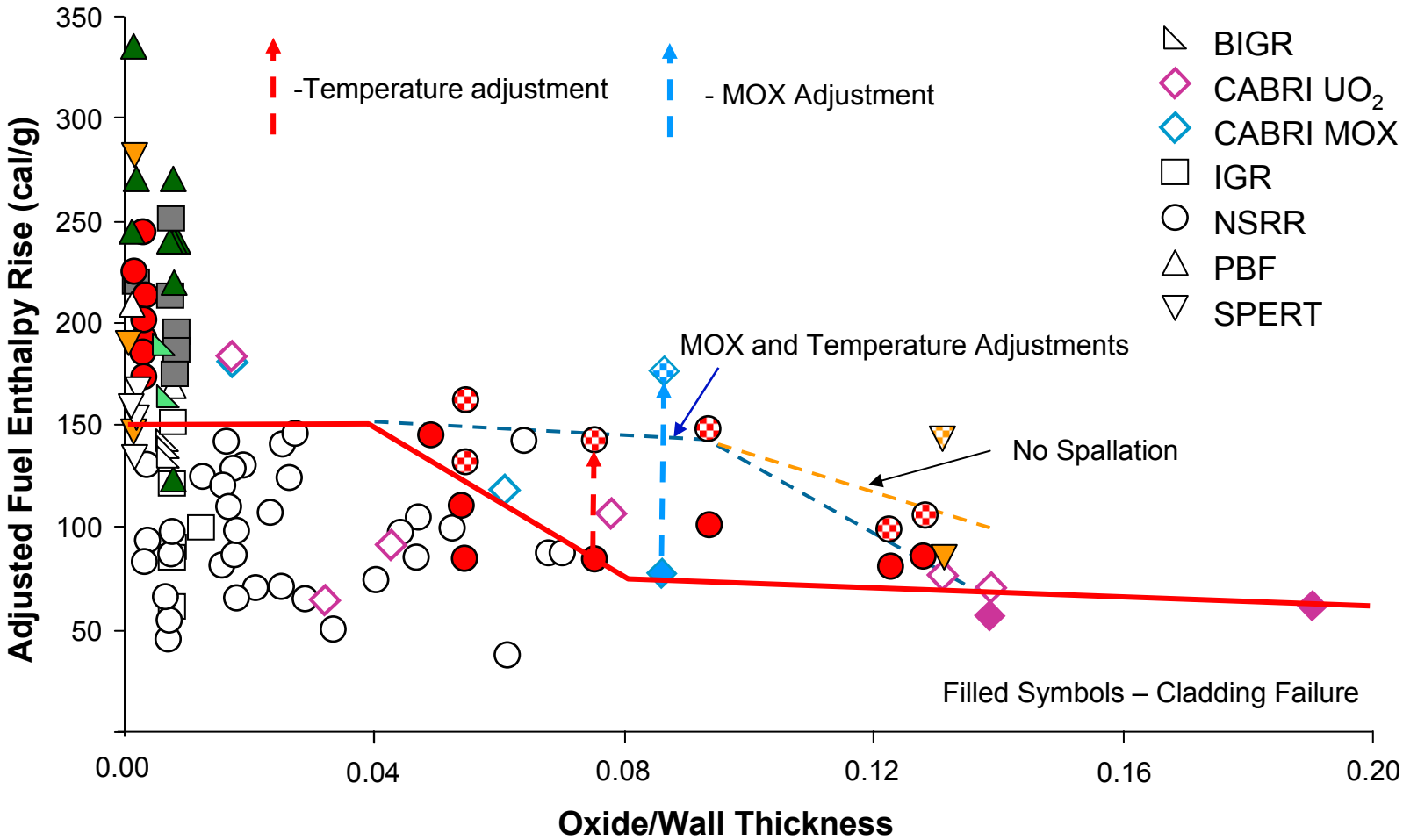
ELECTRIC POWER RESEARCH INSTITUTE

Actions Plan to Scale BWR NSRR Tests

- Use FALCON calculated temperature increase and improvement in cladding ductility
  - Use characteristic BWR power pulse shape
  - Potential increase in fuel enthalpy at failure fpr hydrogen contents between 75 and 250 ppm
- On-going actions
  - Mechanical properties qualifying the ductility improvements with temperature increase
  - Re-calculation of NSRR BWR test with representative power pulse shape

© 2006 Electric Power Research Institute, Inc. All rights reserved.

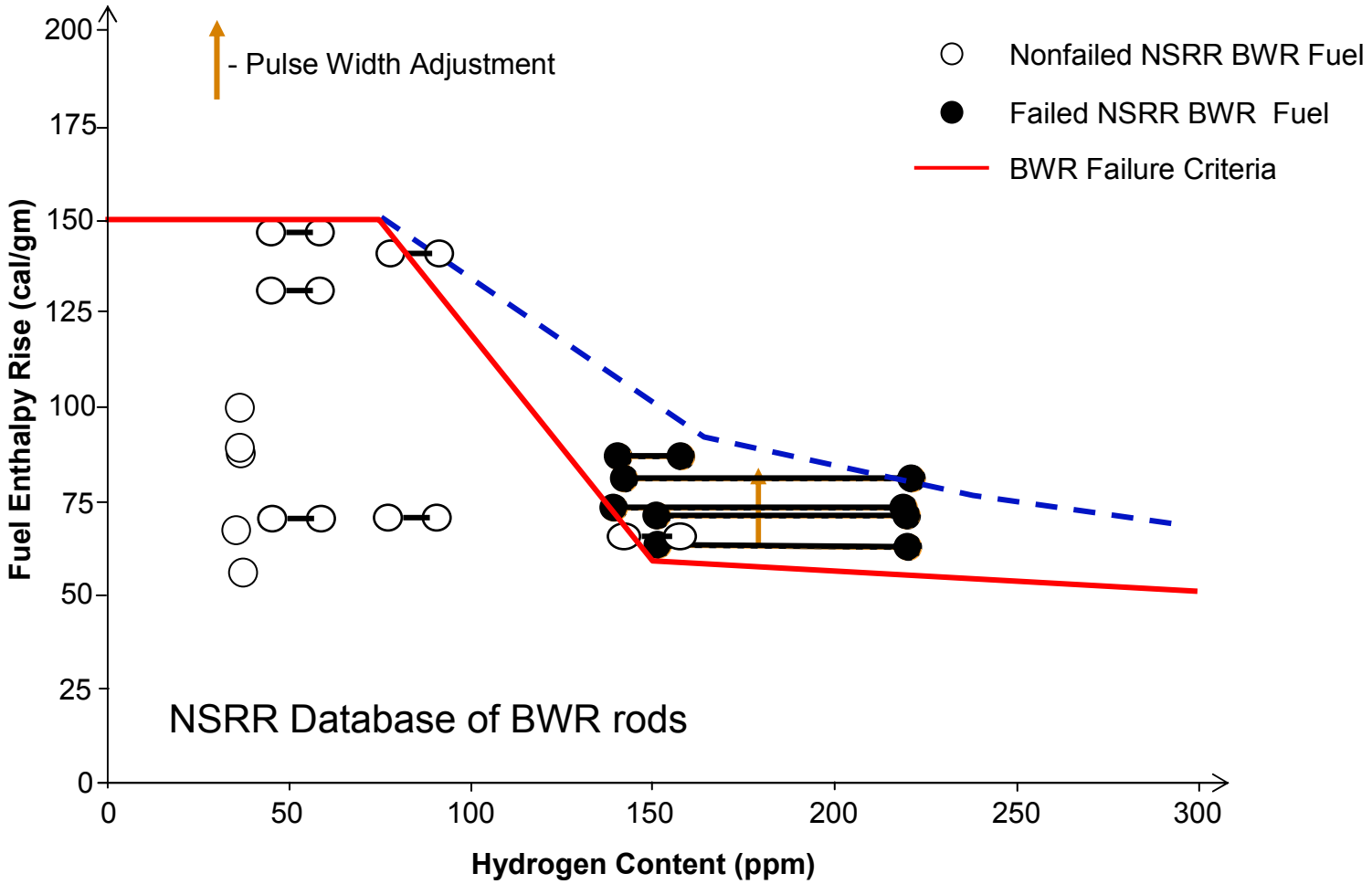
Improved PWR PCMI Failure Criteria



© 2006 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Alternative BWR PCMI Failure Criteria – Improved Consideration for NSRR Tests



© 2006 Electric Power Research Institute, Inc. All rights reserved.

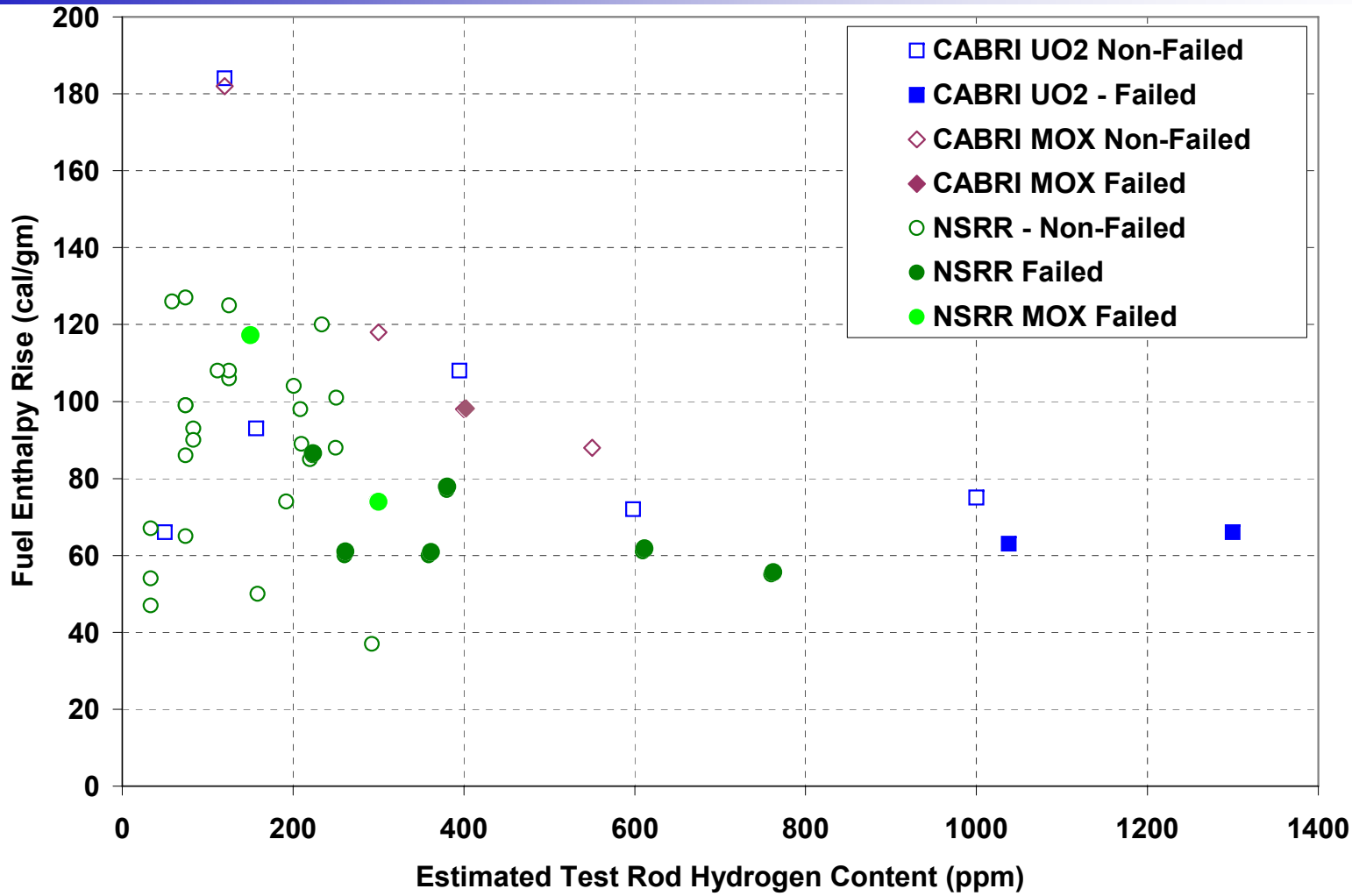
ELECTRIC POWER RESEARCH INSTITUTE

Considerations with Developing Hydrogen Accumulation Models

- Corrosion and hydrogen models would require refinement and approval for RIA licensing
  - Set procedure for hydrogen measurements needed
    - Sample preparation, measurement method, etc…
  - Database of clad oxide thickness over a range of burnup, fuel duty, and coolant chemistry conditions
    - Hot cell investigations initially required to generate the data for models
- Direct correlation of cladding hydrogen concentration to oxide thickness not always achievable for BWR cladding
  - Zry-2 hydrogen content cannot be readily deduced from oxide thickness and hot cell examination is currently required to get hydrogen data
- How to account for hydride distribution and orientation
  - Circumferential vs Radial vs Hydride lens

© 2006 Electric Power Research Institute, Inc. All rights reserved.

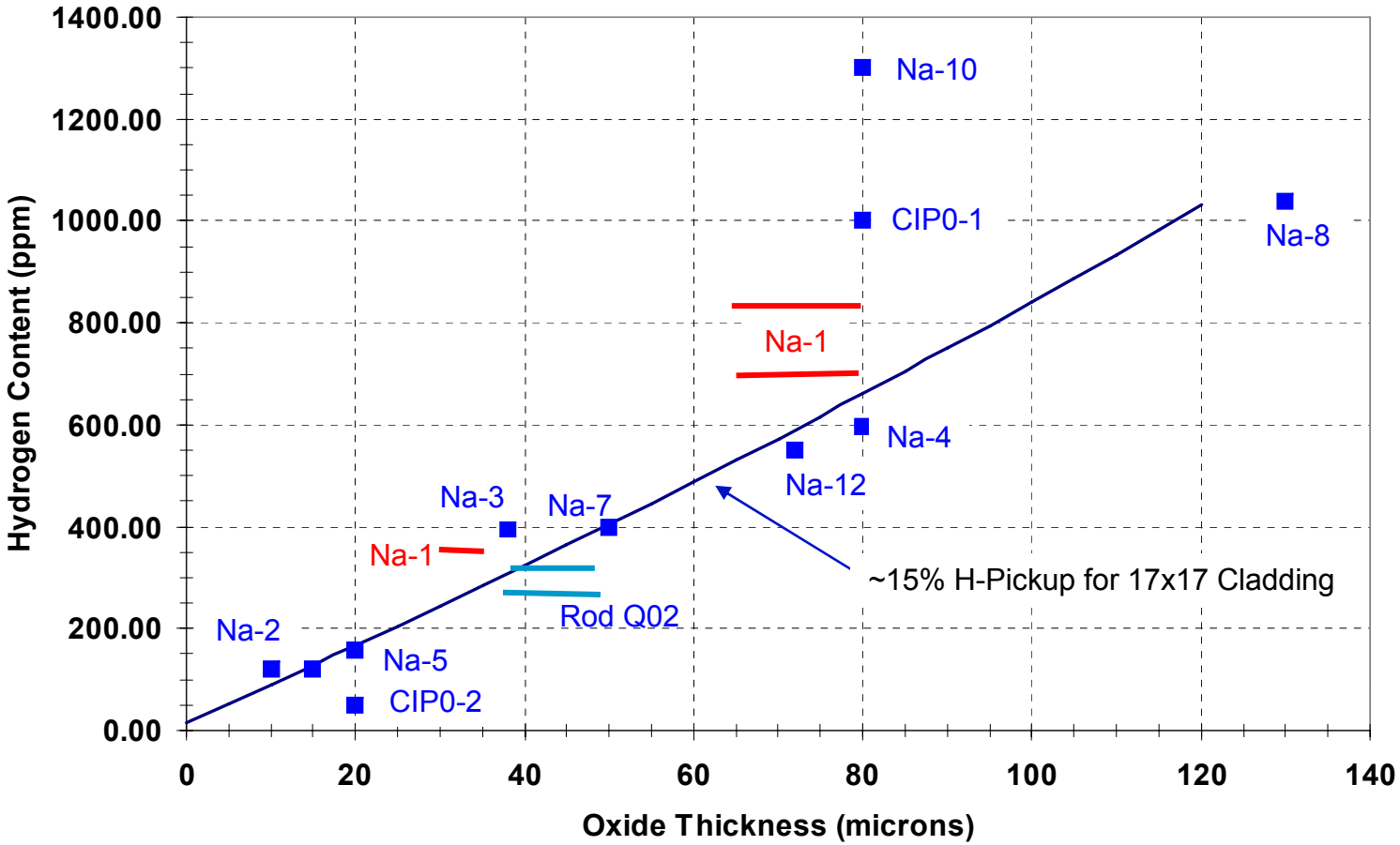
PWR RIA Database as Function of Hydrogen



© 2006 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

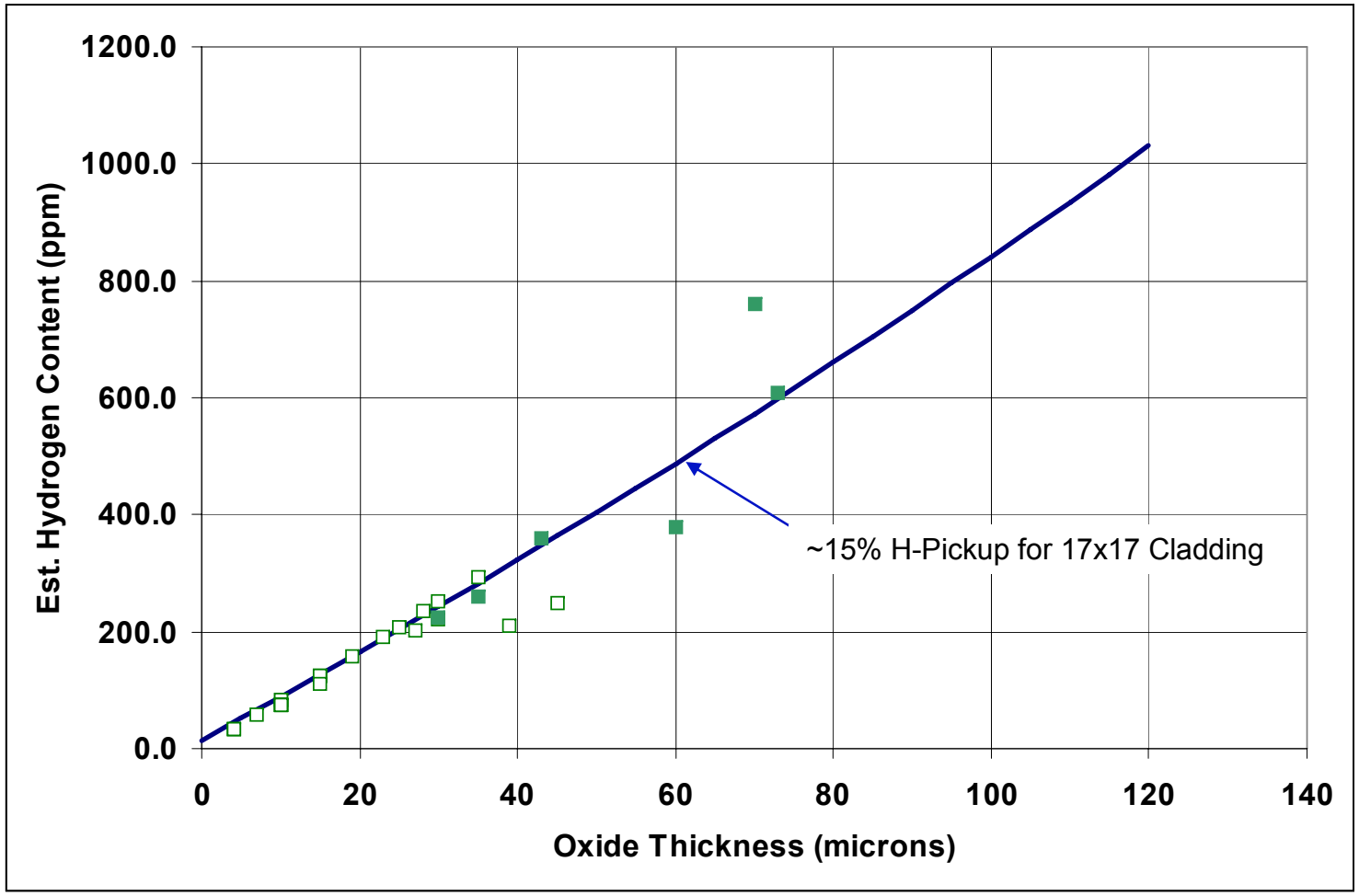
Cladding Hydrogen Content Estimates - CABRI



© 2006 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Cladding Hydrogen Content Estimates - NSRR



© 2006 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Summary of Improvements to Final Failure Criteria

- Newer experimental data and fully qualified analytical methods can improve data adjustments to account for;
  - Improved cladding ductility with increase in temperature and hydrogen solubility effects
  - More severe loading response in irradiated MOX fuel pellet
  - BWR pulse width effects
- Assessment and comparison of analytical methodologies to determine best approach temperature scaling
  - Use to develop acceptable data adjustment factors
- Potential increase in fuel enthalpy at failure
  - PWR PCMI → oxide thickness levels between 25 and 60 μm
  - BWR PCMI → hydrogen contents between 75 and 250 ppm

© 2006 Electric Power Research Institute, Inc. All rights reserved.