Proposed Changes in Regulation for LOCA and RIA in the US

Fuel Safety Research Meeting
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NRC's current regulations on LOCA

§ 50.46 Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors.

Commission hearings in the 1970's established that coolable geometry could be accomplished if the fuel **cladding remained ductile.**

Therefore criteria were established to ensure ductility, and these criteria are specified in the rule. The criteria state:

- The calculated maximum fuel element cladding temperature **shall not exceed 2200º F**.
- The calculated **total oxidation** of the cladding **shall nowhere exceed 0.17** times the total cladding thickness before oxidation.

Question (circa 1996): Are these criteria still appropriate for high burnup cladding?

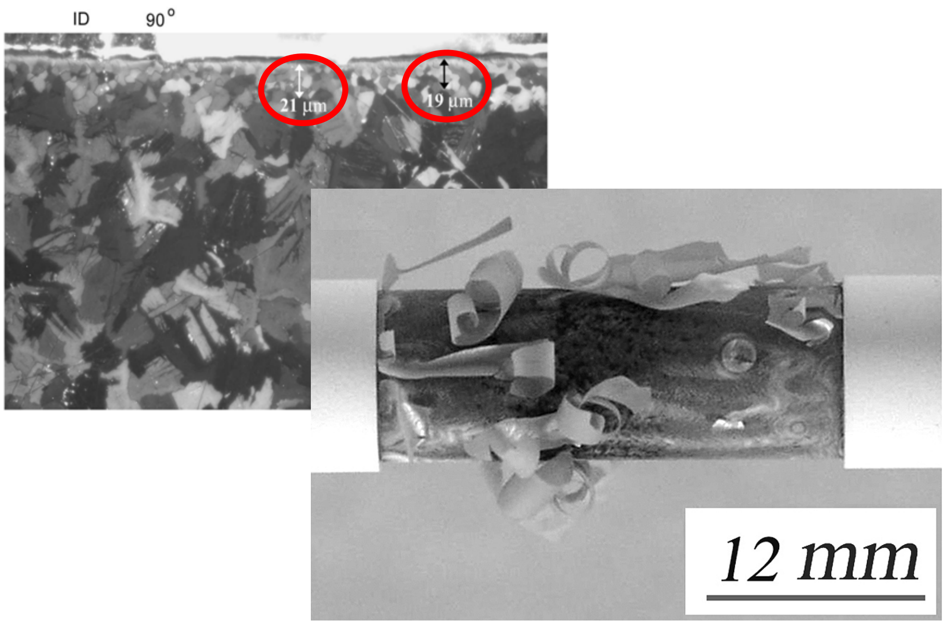
- Calculated **changes in core geometry** shall be such that the core remains amenable to cooling.
- Calculated core temperature shall be maintained **at an acceptably low value** and decay heat shall be removed for the long term.

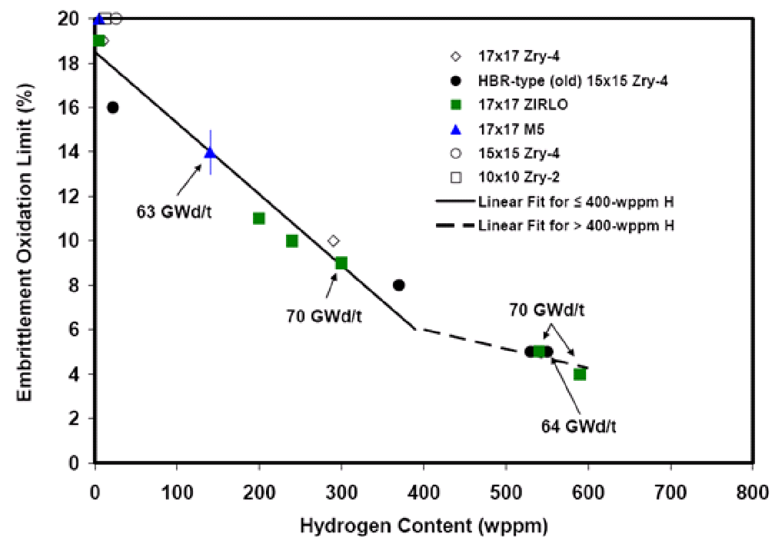
Question raised by GSI-191 & STP pilot: Does this include consideration of debris and can risk informed methods be used to evaluate?

Research Findings

New embrittlement mechanisms were identified for high burnup cladding that are not included in the current rule:

1. Hydrogen-enhanced beta layer embrittlement.
2. Cladding ID oxygen diffusion
3. Breakaway oxidation

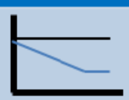




50.46c Rulemaking Drivers

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Drivers
Research

Changes

Hydrogen

Breakaway oxidation requirement

ID oxidation requirement

Supporting Documents
RG 1.222	RG 1.223	RG 1.224	NUREG /CR-6967	RIL-0801	NUREG-2119	Supp. to RIL-0801

Drivers
SRM-SECY-02-0057

PRM-50-71

Changes
Restructured rule.

Removal of cladding names

Performanced-based phrasing

Drivers
PRM-50-84

Changes
CRUD requirement

Drivers
GSI-191

SRM-SECY-12-0034

Changes
Risk-informed alternative for debris in LTC.

Supporting Documents
RG 1.229

50.46c Requirements - Unchanged

- Peak cladding temperature criterion, 2200 ^{o}F
- Core wide oxidation criterion, 1.0%
- Requirement to address effects of debris in sump

50.46c Requirements - New

- Hydrogen-dependent cladding embrittlement criteria; integral time-at-temperature and peak cladding temperature
- Breakaway oxidation test requirement
- Cladding ID oxygen ingress analytical requirement
- Crud thermal conductivity analytical requirement
- No further cladding damage during long-term cooling
  - Debris induced post-quench reheat transient necessitates fuel performance testing
- Alternative risk-informed approach for treatment of debris

50.46c Restructuring

Old Rule

Implied or underlying requirements
- Ductility = Coolable geometry
- Fuel acceptance criteria = ECCS performance requirements

Stated Requirements
- Remain below 17% Oxidation
- Remain below 2200° F

Applicability
- Uranium Oxide fuel with
  - Zircaloy or
  - ZIRLO

New Rule

Stated Requirements
- ECCS performance requirements are separate from
- Fuel acceptance criteria
  - Ductility is a means of ensuring coolable geometry for Zr-UO2/MOX

Regulatory Guidance
- Provides performance-based approaches to meet fuel acceptance criteria

Applicability
- All fuel in LWRs
- Specific requirements available for UO2 and MOX in all cylindrical zirconium alloys

Risk-Informed Alternative

Five key things to know about the RI alternative

1. Optional
2. Compares risk from as-built, as operated plant to hypothetical “clean plant” with no debris
3. Follows RG 1.174 approach + additional requirements for reporting, changes / errors, and updates to model
4. Use of risk is restricted only to the effects of debris on long term core cooling
5. Written at a high level. Detailed guidance contained in RG 1.229.

Fuel Fragmentation, Relocation and Dispersal (FFRD)

- NRC Commission requested staff to determine if any provisions for FFRD needed to be added to the new LOCA rule.
- The staff determined that no new requirements were needed at this time, primarily due to the current limitations on burnup in the US.
- Nevertheless…
  - NRC continues multilateral research activities and interactions with stakeholders with the goal of developing a regulatory framework to address FFRD, if needed, in the next few years.
  - Without definition of the ultimate boundary of safe operation, it is challenging to evaluate the acceptability of future fuel design advancements and fuel utilization changes.

For more information on revisions to LOCA criteria, see

1. RG 1.222, Conducting Periodic Testing for Breakaway Oxidation Behavior (ML16005A135)
2. RG 1.223, Testing for Post-Quench Ductility (ML16005A134)
3. RG 1.224, Establishing Analytical Limits for Zirconium-Based Alloy Cladding (ML16005A133)
4. RG 1.229, Alternate Risk-Informed Approach for Addressing the Effects of Debris on Post-Accident Long-Term Cooling" (ML16102A163)
5. NUREG/CR-6967, Cladding Embrittlement During Postulated Loss-of-Coolant Accidents (ML082130389)
6. NUREG/CR-7219, Cladding Behavior during Postulated Loss-of-Coolant Accidents (ML16211A004)
7. Research Information Letter 0801, "Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46," (ML081350225)
8. NUREG-2119, Mechanical Behavior of Ballooned and Ruptured Cladding (ML12048A475)
9. Update to Research Information on Cladding Embrittlement Criteria in 10 CFR 50.46 [Update to RIL-0801] (ML113050484)
10. SECY-15-0148: Evaluation of Fuel Fragmentation, Relocation and Dispersal Under Loss-of-Coolant Accident (LOCA) Conditions Relative to the Draft Final Rule on Emergency Core Cooling System Performance During a LOCA (50.46c) (ML15230A200)
11. Proposed Rule Package, including description of the proposed rule, discussion of changes and responses to all comments received during the public comment period. (ML15238A947)

U.S.NRC — NRC's RIA acceptance criteria

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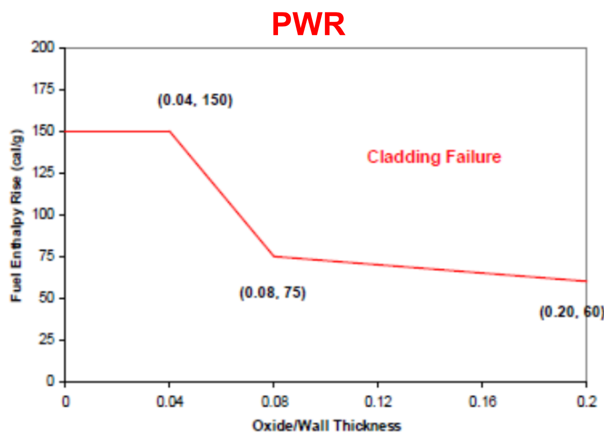
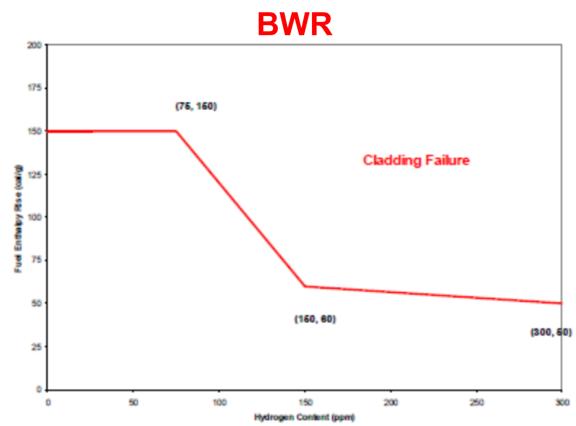
- Cladding Failure – High Temperature Cladding Failure
  - peak radial average fuel enthalpy must be <170 cal/g for rods with RIP below system pressure
  - peak radial average fuel enthalpy must be <150 cal/g for rods with RIP above system pressure

- Cladding Failure – Hydrogen-enhanced PCMI Cladding Failure





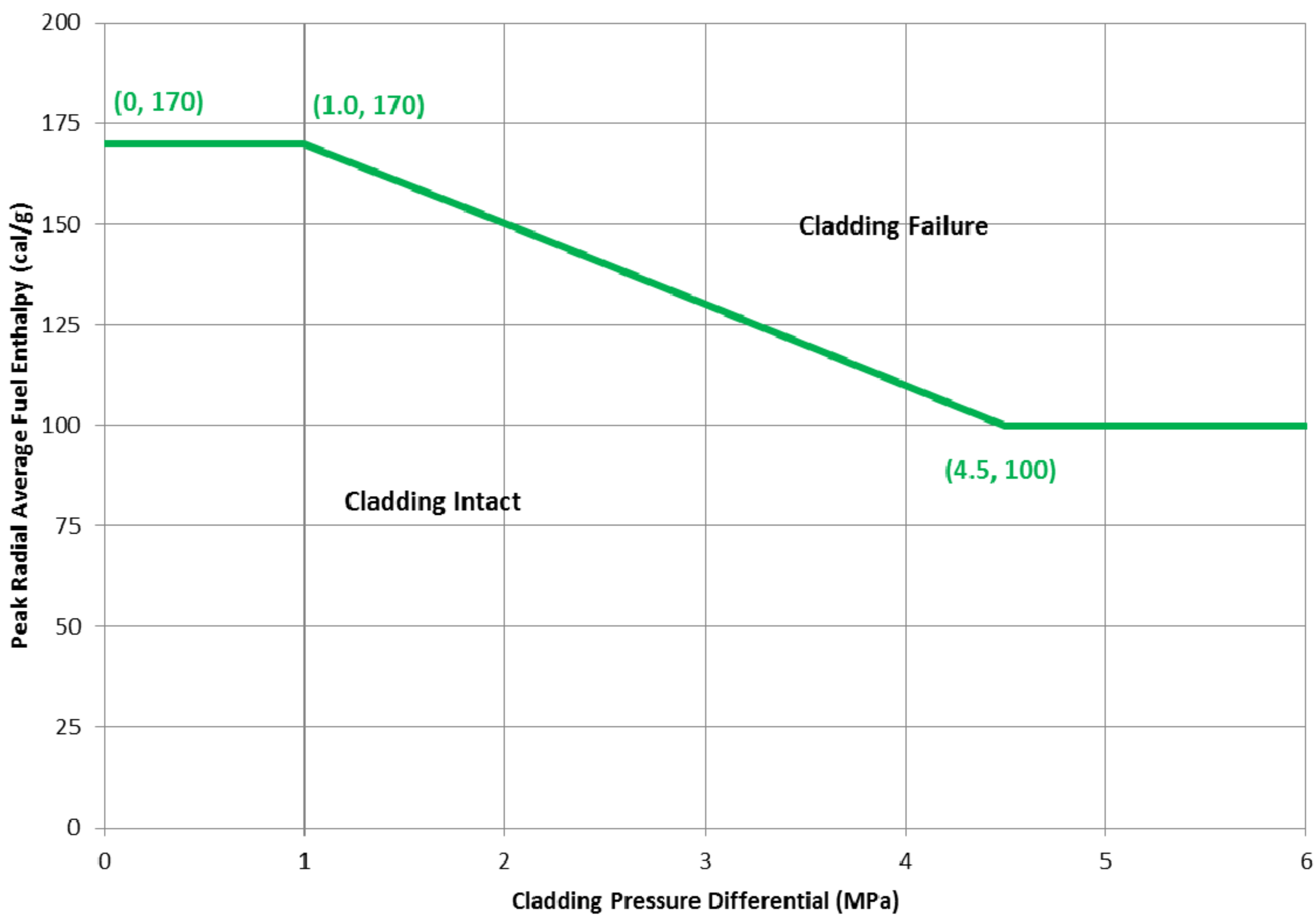
- Coolable Geometry –
  - Peak radial average fuel enthalpy must be less than 230 cal/g
  - Peak fuel temperature must be below incipient fuel melting conditions
  - Mechanical energy generated as a result of (1) non-molten fuel-to-coolant interaction and (2) fuel rod burst must be addressed with respect to reactor pressure boundary, reactor internals, and fuel assembly structural integrity.
  - No loss of coolable geometry due to (1) fuel pellet and cladding fragmentation and dispersal and (2) fuel rod ballooning.

Research on high burnup fuel RIA performance

- The following information has become available which has prompted the NRC to update portions of the Interim RIA Criteria and Guidance (SRP 4.2 Appendix B, 2007):
  - OECD Nuclear Energy Agency State-of-the-art Report, "Nuclear Fuel Behaviour under Reactivity-initiated Accident Conditions," 2010.
  - EPRI Report 1021036, "Fuel Reliability Program: Proposed RIA Acceptance Criteria," December 2010.
  - Revised RIA transient fission gas release fractions (DG-1199).
  - PNNL Report 22549, "Pellet-Cladding Mechanical Interaction Failure Threshold for Reactivity Initiated Accidents for Pressurized Water Reactors and Boiling Water Reactors," June 2013.
  - Published results from NSRR Hot Capsule RIA Tests, including VA3, VA4, RH2, BZ3, and LS2.
  - JAEA published revised test results for 43 previous NSRR tests.

Proposed revisions to RIA requirements

High Temperature Cladding Failure



The revised criteria maintain the upper high temperature failure threshold of 170 cal/g, combined with consideration of the cladding differential pressure relationship, accounting for both the oxidation-induced embrittlement and balloon and burst failure modes.

Predicted cladding differential pressure must consider the impact of transient FGR on internal gas pressure.

For intermediate and full power conditions, fuel cladding failure is presumed if local heat flux exceeds thermal design limits (e.g. DNBR and CPR).

Proposed revisions to RIA requirements

Hydrogen Enhanced PCMI Failure

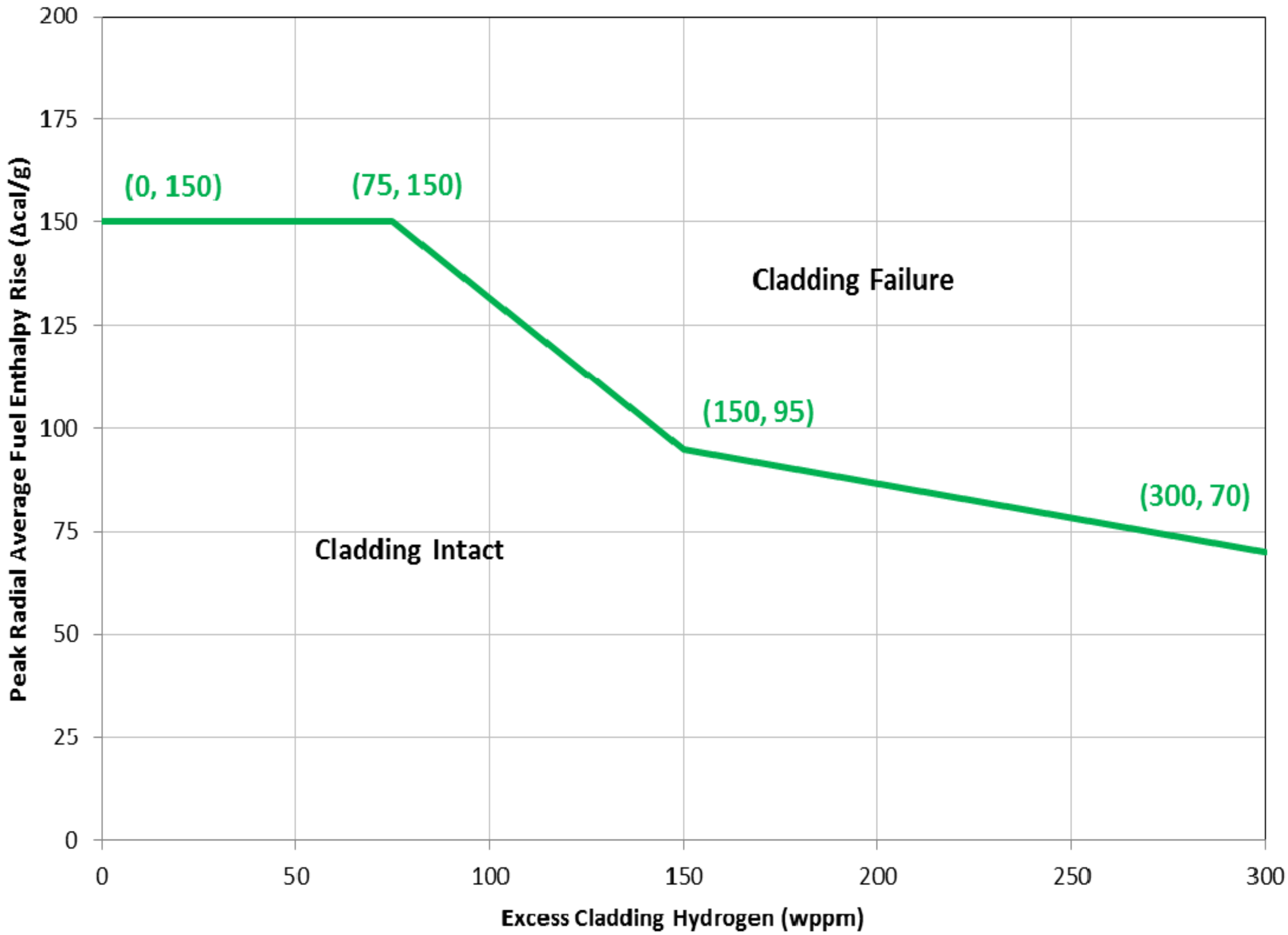
- The effect of hydride orientation (radial vs. circumferential) is significant.
  - Separate PCMI failure limits for CWSR and RXA cladding alloys.
  - For each cladding alloy, the hydride distribution and orientation must be characterized to determine applicability of PCMI failure curves.

- The effect of initial cladding temperature was quantified.
  - Comparison of NSRR hot capsule results with original cold test results reveal an 18 cal/g scaling factor for temperature effects.
  - Separate PCMI failure limits for “hot” PWR and “cold” BWR conditions.

Proposed revisions to RIA requirements

Hydrogen Enhanced PCMI

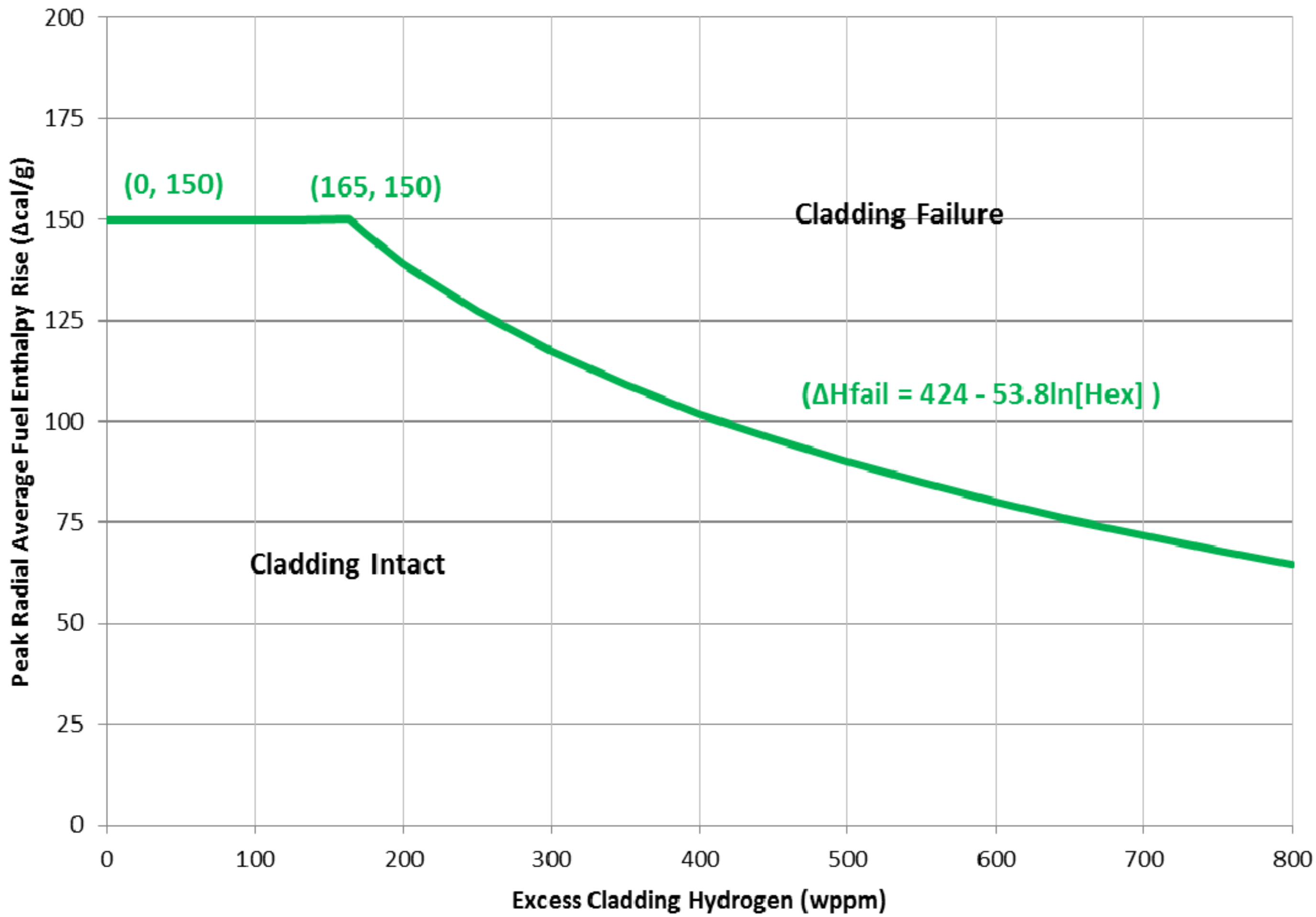
RXA Cladding, PWR Operating Conditions



Proposed revisions to RIA requirements

Hydrogen Enhanced PCMI

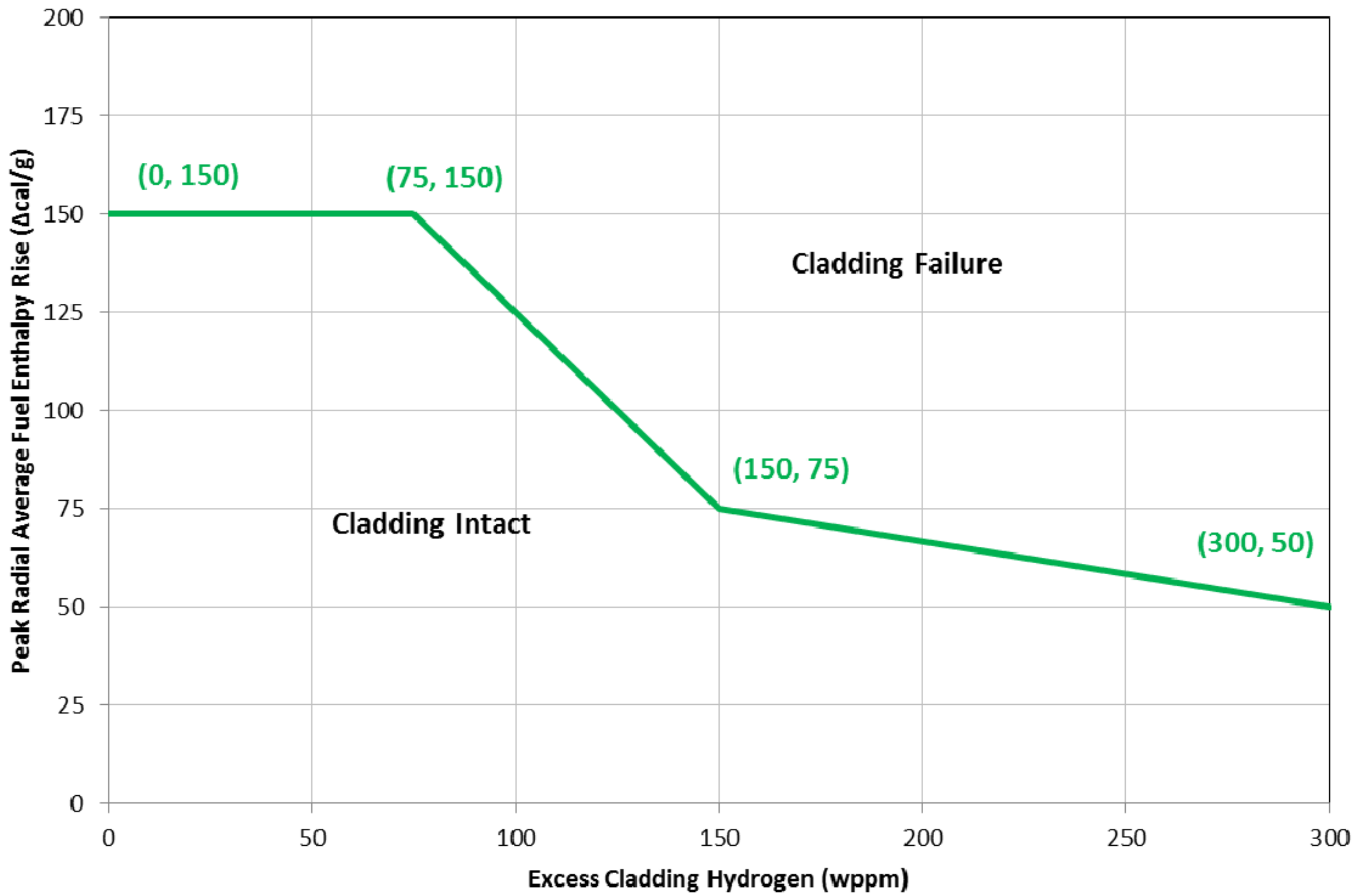
SRA Cladding, PWR Operating Conditions



Proposed revisions to RIA requirements

Hydrogen Enhanced PCMI

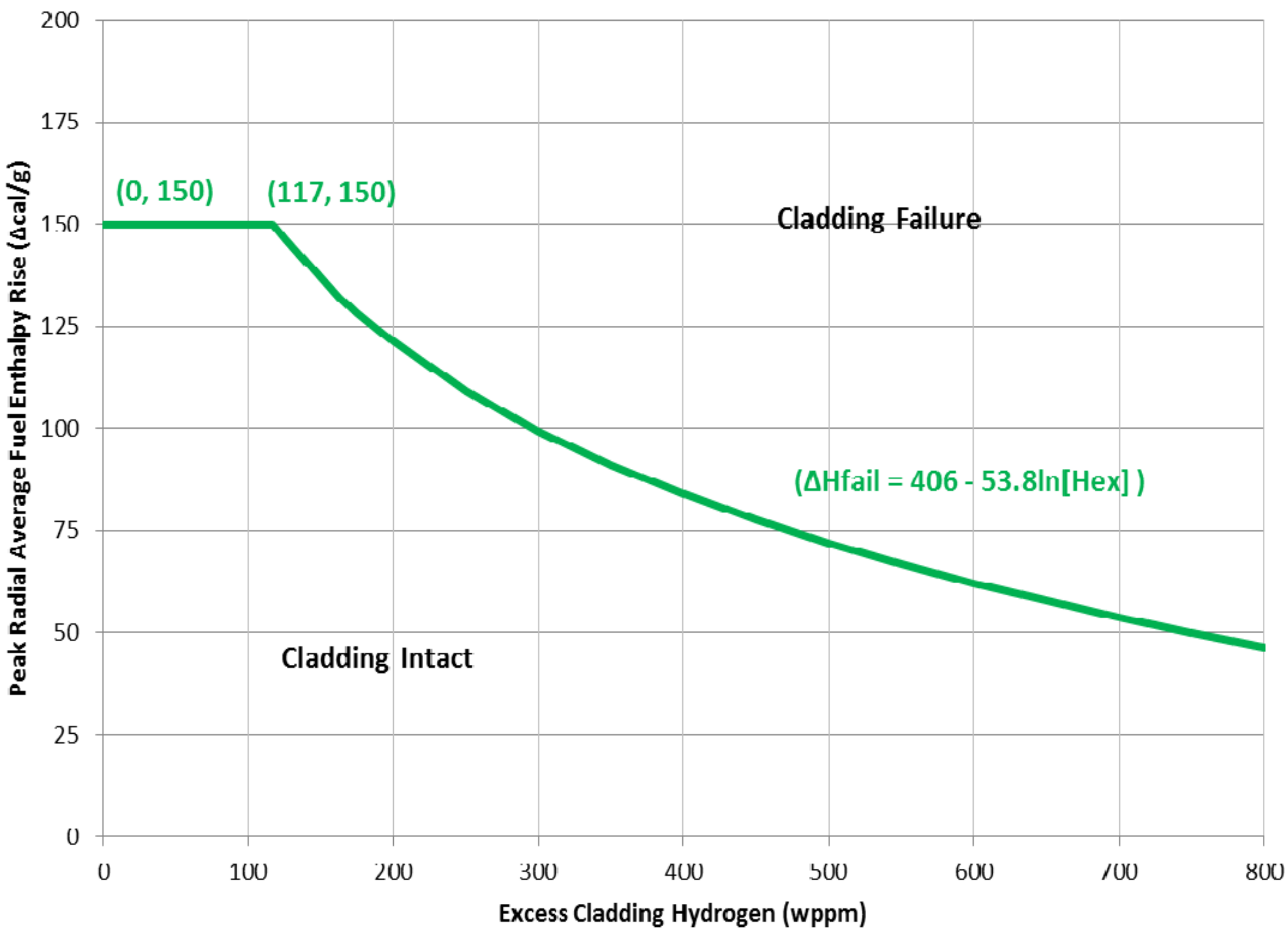
RXA Cladding, BWR Cold Startup Conditions



Proposed revisions to RIA requirements

Hydrogen Enhanced PCMI

SRA Cladding, BWR Cold Startup Conditions



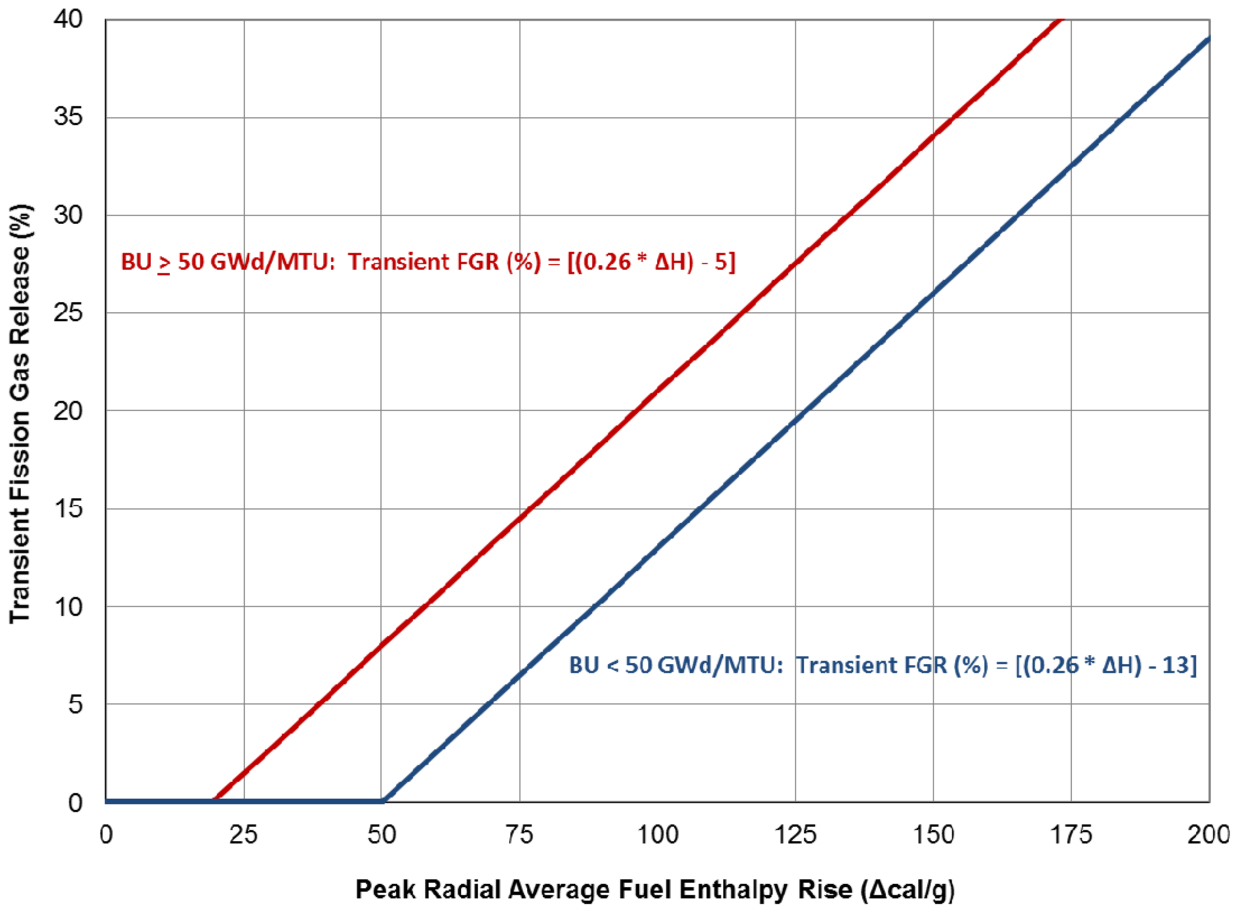
Proposed revisions to RIA requirements

Coolability Criteria

- Peak radial average fuel enthalpy must remain < 230 cal/g.
- A limited amount of fuel melting is acceptable provided it is restricted to (1) fuel centerline region and (2) less than 10% of pellet volume. For the outer 90% of the pellet volume, peak fuel temperature must remain below incipient fuel melting conditions.

Proposed revisions to RIA requirements

Fission Product Inventory



Revised BU-dependent transient (fragmentation-induced) FGR correlations based on revised NSRR data.

For more information on revisions to RIA criteria, see

- Clifford, P. M., "Technical and Regulatory Basis for the Reactivity Initiated Accident Acceptance Criteria and Guidance, Revision 1," March 16, 2015 (ML14188C423)
- PNNL Report 22549, "Pellet-Cladding Mechanical Interaction Failure Threshold for Reactivity Initiated Accidents for Pressurized Water Reactors and Boiling Water Reactors," June 2013 (ADAMS ML13277A368).
- Forthcoming Draft Guide (DG) 1327 is scheduled to be available for public comment later this year. It will replace RG 1.77 and Standard Review Plan section 4.2, Appendix B

Conclusions

- Fuel performance under LOCA and RIA conditions are two areas where NRC is now making regulatory changes to address issues uncovered after initial operation of high burnup / high duty fuel.

- These issues have highlighted the importance of ongoing research and experiments characterizing fuel behavior under limiting conditions PRIOR to additional burnup extensions.