UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, DC 20555 - 0001

February 23, 2016

The Honorable Stephen G. Burns
Chairman
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: DRAFT FINAL RULE 10 CFR 50.46c, "EMERGENCY CORE COOLING SYSTEM PERFORMANCE DURING LOSS-OF-COOLANT ACCIDENTS (LOCA)" AND ASSOCIATED REGULATORY GUIDES

Dear Chairman Burns:

During the 631st meeting of the Advisory Committee on Reactor Safeguards, February 4-6, 2016, we completed our review of the draft final rule, 10 CFR 50.46c. We also completed our review of draft Regulatory Guides 1.222, 1.223, and 1.224 that provide guidance for compliance with the fuel performance requirements in the draft final rule. Draft Regulatory Guide 1.229 remains under review. During the meeting, we had the benefit of discussion with representatives of the NRC staff, the Nuclear Energy Institute, the nuclear power plant owners groups, reactor fuel vendors, and the public. Our Metallurgy and Reactor Fuels Subcommittee reviewed this matter on November 3, 2015. We also had the benefit of the documents referenced.

RECOMMENDATIONS

1. The draft final rule 10 CFR 50.46c and associated Regulatory Guides 1.222, 1.223, and 1.224 should be issued.

2. Draft Regulatory Guide 1.229 should not be issued until our review has been completed.

BACKGROUND

Research has established that hydrogen uptake during operation, as well as oxygen ingress during a design basis accident, combine synergistically to degrade cladding ductility. This research implies current requirements do not always ensure adequate post-quench ductility of cladding during a loss of coolant accident (LOCA).

The objective of the draft final rule, 10 CFR 50.46c, is to ensure adequate core coolability in the event of a LOCA. The staff has developed a draft final rule that adopts a performance-based approach to meet emergency core cooling system (ECCS) and fuel performance requirements related to a LOCA, in place of prescriptive requirements. The new rule also allows an alternative risk-informed approach for addressing debris effects on long-term core cooling. These revisions to the rule are consistent with the Commission direction in the Staff Requirements Memorandum (SRM) for SECY-02-0057.

The draft final rule also addressed Petition for Rulemaking PRM-50-71 that requested expanding the applicability of the ECCS rule to include all zirconium alloy cladding. The rule further addressed PRM-50-84 that, among other items, requested a requirement for licensees to account for the thermal effects of crud and oxide layers in their ECCS evaluation models.

The staff has conducted an extensive research program to study the effects of alloy compositions and fuel burnup levels on the embrittlement of zirconium-based cladding alloys during LOCA transients. This included a LOCA research and testing program conducted at Argonne National Laboratory as well as international research programs. The new research results are documented in Research Information Letter 0801 and NUREG/CR-6967. These serve as the technical bases for the proposed rulemaking.

The research found that some of the hydrogen generated by waterside corrosion penetrates the fuel cladding during normal operation and promotes cladding embrittlement in the event of a LOCA. Since the acceptance criteria in the current rule do not consider the effects of fuel burnup and corrosion-induced absorption of hydrogen in the cladding, the current requirements may not always ensure adequate post-quench ductility of cladding during a LOCA. The research results also confirmed a previous finding that, if cladding rupture occurs during a LOCA, a large amount of hydrogen produced from the steam-cladding reaction can enter the cladding inside surface near the rupture location. The fuel cladding research further identified breakaway oxidation[1] as a potential embrittlement mechanism during a LOCA. The draft final rule accounts for these research findings on fuel cladding embrittlement behavior.

On March 24, 2014, the NRC published the proposed rule, 10 CFR 50.46c, with associated draft regulatory guides regarding fuel performance criteria for public comments. Subsequently, the NRC received public comments and held several public meetings with stakeholders. As part of these rulemaking activities, the NRC staff developed four companion regulatory guides that provide acceptable approaches and methods for compliance with the new rule. Three of the draft regulatory guides provide guidance for the implementation of fuel-specific analytical limits and associated tests: 1) 1.222, “Measuring Breakaway Oxidation Behavior,” 2) 1.223, “Measuring Post-Quench Ductility,” and 3) 1.224, “Establishing Analytical Limits for Zirconium-Alloy Cladding Material.” The fourth draft regulatory guide, 1.229, “Risk-Informed Approach for Addressing the Effects of Debris on Post-Accident Long-Term Core Cooling,” is still under our review.

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1 Breakaway oxidation is associated with a tetragonal-to-monoclinic phase transformation, which initiates near the metal-oxide interface during steam oxidation of zirconium-based alloys. The rapid oxidation also causes cracks in the monoclinic phase that, in turn, increase cladding absorption of hydrogen generated from the steam-cladding oxidation reaction during a LOCA.

NRC's LOCA Research Program

In Research Information Letter 0801, the staff recommended that the experimental results from the NRC's LOCA research program should be considered as the bases for rulemaking to revise the ECCS performance requirements. In addition, NUREG/CR-6967 describes the results of ring-compression tests and LOCA integral tests to evaluate the effect of fuel burnup on the embrittlement of various zirconium-based cladding alloys under LOCA conditions. The tested specimens were prepared from as-fabricated cladding; pre-hydrided cladding (representing high burnup cladding in terms of corrosion-induced hydrogen absorption); and high burnup cladding that had been irradiated in commercial reactors. The tested alloys included Zircaloy-2, Zircaloy-4, ZIRLO™ and M5™. As-fabricated cladding materials (with no hydrogen absorption other than trace hydrogen) showed a ductile-to-brittle transition consistent with the current 10 CFR 50.46 limit.

The test results demonstrated that the embrittlement levels of zirconium alloy cladding under LOCA conditions were well correlated with an equivalent cladding reacted (ECR) parameter that was calculated using the Cathcart-Pawel oxidation correlation (CP-ECR). This observation supported the conclusion that CP-ECR can quantitatively characterize the effects of high temperature steam oxidation on cladding embrittlement during LOCA transients. In addition, the tests found that the cladding absorption of hydrogen from corrosion during normal operation (i.e., pre-transient hydrogen content) also affects the degree of cladding embrittlement and thus the allowable CP-ECR.

The increased breakaway oxidation rate accelerates hydrogen pickup. Hydrogen that enters in this manner has the same effect on embrittlement as hydrogen absorption due to waterside corrosion during normal operation. The new rule and associated regulatory guides consider this new embrittlement mechanism. Specifically, the draft final rule requires the measurement of breakaway oxidation behavior for zirconium alloy cladding materials to verify that embrittlement limits are not exceeded during a plant-specific LOCA transient.

In addition, the LOCA integral tests reported in NUREG/CR-6967 evaluated the effect of hydrogen that enters the inner surface of the cladding during a LOCA in which the cladding experiences ballooning and burst prior to high temperature steam oxidation. Results demonstrated that sufficient toughness to prevent cladding fragmentation is maintained up to the oxidation limit of 17 percent CP-ECR for cladding in the balloon region. The test results also indicated that the strength or fracture toughness of the balloon region decreases as the oxidation level increases. NUREG-2119 presents the results of four-point bend tests to determine the resistance of ballooned cladding to fracture. The tests included ballooned and ruptured regions of as-fabricated and irradiated cladding following exposure to LOCA conditions. The test results supported the contention that limiting oxidation in the ballooned and ruptured region is appropriate to maintain resistance to failure and that the CP-ECR limit decreases with increasing burnup to account for pre-transient hydrogen absorption. The test report also recommended that the integral time-at-temperature limit, based on ring-compression test data to limit oxidation, should be applied uniformly to the entire rod. The average wall thickness in the ballooned region should be used to calculate the CP-ECR.

The staff used the new research findings on fuel cladding embrittlement behavior appropriately as the technical basis for revising the ECCS fuel performance requirements.

Updates on Fuel Fragmentation, Relocation, and Dispersal

SRM-SECY-12-0034 states that the staff should complete its research on fuel fragmentation, relocation, and dispersal (FFRD) and incorporate any necessary changes before requesting Commission approval of the draft final rule. The SRM also states that the staff should inform the Commission if this action is not practicable or has unintended consequences. During our meetings, the staff indicated that the 10 CFR 50.46c Rulemaking Working Group recommended against adding a new requirement in the 10 CFR 50.46c rule related to dispersal of sufficiently fine fuel fragments upon clad ballooning and rupture. The staff also indicated that the Rulemaking Working Group proposal was approved by the 10 CFR 50.46c Rulemaking Steering Committee. The staff provided the following basis for not including FFRD in the 10 CFR 50.46c rule, which is discussed in Information SECY-15-0148:

- Reasonable assurance that no imminent safety concern exists.

- FFRD phenomena may not be restricted to LOCAs, and could be postulated during non-LOCA design basis accidents. Future regulatory action, if needed, should be developed and implemented in a holistic manner to address both LOCA and non-LOCA scenarios.

- Fuel performance requirements, unlike ECCS performance requirements, could be developed to focus on preventing rupture in rods susceptible to fine fuel fragmentation and fuel dispersal, while avoiding unnecessary restrictions on rods that are not susceptible to fine fuel fragmentation.

- Adding new analytical requirements for FFRD into the draft final 10 CFR 50.46c rule would delay implementation of revised requirements that are necessary to assure adequate protection to the public health and safety.

The staff's basis for not including FFRD in the 10 CFR 50.46c rule is appropriate.

DISCUSSION

As previously discussed, the staff used the experimental results from the NRC's LOCA research program as the basis to amend the ECCS performance rule. The draft final rule replaces the existing prescriptive ECR limit with performance-based limits for zirconium alloy cladding under LOCA conditions. The rule further expands the applicability of the cladding acceptance criteria to all fuel designs and cladding materials for light water reactors rather than being limited to fuel using Zircaloy and ZIRLO™ cladding. In addition, the rule allows for an alternative risk-informed approach to evaluate the effects of debris on long-term core cooling, as directed in the SRM for SECY-12-0034.

The draft final rule includes new fuel performance criteria for zirconium alloy cladding as follows:

- Post-quench ductility. Analytical limits on peak cladding temperature and integral time at temperature shall be established that correspond to the measured ductile-to-brittle transition based upon an NRC-approved experimental method. The calculated maximum fuel element temperature and time at elevated temperature shall not exceed the established analytical limits. Regulatory Guide 1.223 provides an acceptable method for measuring post-quench ductility. Regulatory Guide 1.224 provides an acceptable method for establishing the analytical limits for the measured ductile-to-brittle transition for zirconium-based cladding alloys.

- Breakaway oxidation. An analytical time limit that has been shown to preclude breakaway oxidation, using an NRC-approved experimental method, must be determined and specified for each zirconium alloy cladding material. The total time that the cladding is predicted to remain above a temperature at which the zirconium alloy has been shown to be susceptible to breakaway oxidation shall be less than the analytical time limit. Regulatory Guide 1.222 provides an acceptable method for the measurement and periodic confirmation of breakaway oxidation behavior.

In addition, the draft final rule includes requirements for an ECCS evaluation model, consistent with the research findings and PRM-50-84 as described below:

- Oxygen source from the inside surface. If an oxygen source is present on the inside surfaces of the cladding at the onset of the LOCA, the effects of oxygen diffusion from the cladding inside surfaces into the bulk alloy must be considered in the ECCS evaluation model.

- Thermal effects of crud and oxide layers. The thermal effect of oxide and crud that accumulates on the fuel cladding during plant operation must be evaluated.

The draft final rule requires that the breakaway oxidation behavior of zirconium alloy cladding materials must be confirmed periodically using an NRC approved experimental method. The experimental method must be capable of determining the effect of composition changes or manufacturing changes on the breakaway oxidation behavior. In addition, Regulatory Guide 1.222 states that one approach to provide reasonable assurance that fuel is being manufactured consistent with the analytical limits would be to conduct periodic breakaway oxidation measurements on cladding samples from each zirconium alloy ingot. The Regulatory Guide also states that, if other sample populations or test frequencies are used, they must be identified and justified in the confirmatory testing program plan submitted for the staff's review and approval.

The draft final rule requires that each licensee shall submit an implementation plan within six months after the effective date of the rule. Upon receipt of the implementation plan, the staff would work with licensees to prioritize and balance workload, agreeing to plant-specific implementation plans. The rule further requires that all license amendment requests must be submitted no later than 60 months after the effective date of the rule and compliance must be completed no later than 84 months after the effective date of the rule. These milestones are based upon an integrated implementation plan supplied by the industry.

The staff continues to work with licensees to develop and manage an optimized implementation plan for the existing fleet of operating reactors that minimizes cost and operational impact. The staff is working with industry to develop additional guidance for implementing the rule.

SUMMARY

The proposed 10 CFR 50.46c rule responds to significant advances in our understanding of the behavior of zirconium alloy clad fuel under LOCA conditions at high burnup. It maintains the 2200°F upper temperature limit as well as the 1 percent fuel cladding reacted limit, while accounting for burnup effects on cladding ductility. The rule should be issued.

Sincerely,

/RA/

Dennis C. Bley
Chairman

REFERENCES

1. U.S. Nuclear Regulatory Commission, Federal Register Notice, “Performance-Based Emergency Core Cooling System Requirements And Related Fuel Cladding Acceptance Criteria (10 CFR Parts 50 and 52, RIN 3150-AH42),” January 19, 2016 (ML16005A128).

2. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.222 (draft), “Measuring Breakaway Oxidation Behavior,” January 19, 2016 (ML16005A135).

3. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.223 (draft), “Determining Post Quench Ductility,” January 19, 2016 (ML16005A134).

4. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.224 (draft), “Establishing Analytical Limits for Zirconium-Alloy Cladding Material,” January 19, 2016 (ML16005A133).

5. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.229 (draft), “Risk-Informed Approach for Addressing the Effects of Debris on Post-Accident Long-Term Core Cooling,” December 1, 2015 (ML15335A179).

6. U.S. Nuclear Regulatory Commission, SRM-SECY-02-0057, "Update to SECY-01-0133, 'Fourth Status Report on Study of Risk-informed Changes to the Technical Requirements of 10 CFR Part 50 (Option 3) and Recommendations on Risk-informed Changes to 10 CFR 50.46 (ECCS Acceptance Criteria)'," March 31, 2003 (ML030910476).

7. U.S. Nuclear Regulatory Commission, Research Information Letter 0801, "Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46," May 30, 2008 (ML081350225).

8. U.S. Nuclear Regulatory Commission, NUREG/CR-6967, "Cladding Embrittlement During Postulated Loss-of-Coolant Accidents," July 31, 2008 (ML082130389).

9. U.S. Nuclear Regulatory Commission, NUREG-2119, "Mechanical Behavior of Ballooned and Ruptured Cladding," February 29, 2012 (ML12048A475).

10. U.S. Nuclear Regulatory Commission, SRM-SECY-12-0034, "Proposed Rulemaking 10 CFR 50.46c: Emergency Core Cooling System Performance During Loss-of-Coolant Accidents (RIN 3150-AH42)," January 7, 2013 (ML13007A478).

11. U.S. Nuclear Regulatory Commission, 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)," November 30, 2015 (ML15230A200).

12. U.S. Nuclear Regulatory Commission, "NRC Staff Responses to Public Comments on Proposed Rule: 'Performance-Based Emergency Core Cooling Systems Cladding Acceptance Criteria' and Three Associated Draft Regulatory Guides," January 19, 2016 (ML16005A127).

13. U.S. Nuclear Regulatory Commission, "NRC Staff Responses to Public Comments on DG 1322: 'Risk-Informed Approach for Addressing the Effects of Debris on Post-Accident Long-Term Core Cooling'," October 19, 2015 (ML15292A009).

14. U.S. Nuclear Regulatory Commission, NUREG/IA-0211, "Experimental Study of Embrittlement of Zr-1%Nb VVER Cladding under LOCA-Relevant Conditions," March 31, 2005 (ML051100343).

15. U.S. Nuclear Regulatory Commission, NUREG-2121, "Fuel Fragmentation, Relocation, and Dispersal During the Loss-of-Coolant Accident," March 31, 2012 (ML12090A018).

16. Advisory Committee on Reactor Safeguards, "ACRS Assessment of the Quality of Selected NRC Research Projects - FY 2013," November 21, 2013 (ML13323B189).

17. Advisory Committee on Reactor Safeguards, "Proposed Draft Rule for 10 CFR 50.46c, 'Emergency Core Cooling System Performance During Loss-of-Coolant Accidents'," January 26, 2012 (ML12023A089).

18. Advisory Committee on Reactor Safeguards, "Draft Regulatory Guides DG-1261, DG-1262, and DG-1263," June 22, 2011 (ML11164A048).

19. Advisory Committee on Reactor Safeguards, "Technical Basis and Rulemaking Strategy for the Revision of 10 CFR 50.46(b) Loss-of-Coolant Accident Embrittlement Criteria for Fuel Cladding Materials," December 18, 2008 (ML083460310).

20. Advisory Committee on Reactor Safeguards, "Proposed Technical Basis for the Revision to 10 CFR 50.46 LOCA Embrittlement Criteria for Fuel Cladding Materials," May 23, 2007 (ML071430639).

21. Advisory Committee on Reactor Safeguards, "Draft Final Rule to Risk-Inform 10 CFR 50.46, 'Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors'," November 16, 2006 (ML063190465).

22. Advisory Committee on Reactor Safeguards, "Report on a Proposed Technical Basis for Revision of the Embrittlement Criteria in 10 CFR 50.46," September 23, 2005 (ML052660300).

23. Advisory Committee on Reactor Safeguards, "Risk-Informing 10 CFR 50.46, 'Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors'," December 17, 2004 (ML043580058).

24. Advisory Committee on Reactor Safeguards, "Confirmatory Research Program on High-Burnup Fuel," October 17, 2002 (ML022960640).

25. U.S. Nuclear Regulatory Commission, "Draft Final Rule – Performance-Based Emergency Core Cooling System Requirements and Related Fuel Cladding Acceptance Criteria (RIN 3150-AH42)," January 19, 2016 (ML16005A129).

26. U.S. Nuclear Regulatory Commission, SRM-COMSECY-13-0006, "10 CFR 50.46c Rulemaking: Request to Defer Draft Guidance and Extension Request for Final Rule and Final Guidance," May 9, 2013 (ML13129A401).

27. U.S. Nuclear Regulatory Commission, Regulatory Issue Summary 2015-## (draft), "Clarification of 10 CFR 50.46 Reporting Requirements and Recent Issues with Related Guidance Not Approved for Use by the NRC," July 9, 2015 (ML15057A346).

28. U.S. Nuclear Regulatory Commission, Regulatory Analysis, "Regulatory Analysis for Emergency Core Cooling System Performance during Loss-of-Coolant Accidents Final Rule (10 CFR 50.46c)," January 19, 2016 (ML16005A130).

Appendix: Chronology of the ACRS Review of the 10 CFR 50.46c Rulemaking Activities

The extensive ACRS review of the 10 CFR 50.46c rulemaking activities and its interactions with representatives of the NRC staff, stakeholders and the public are discussed in the following ACRS letters and meeting transcripts.

Date	Meeting/Letter	ADAMS Accession Number
October 9, 2002	Subcommittee Meeting	ML023030246*
October 10, 2002	Full Committee Meeting	ML022980190*
October 17, 2002	Letter from ACRS to NRC Chairman	ML022960640
December 9, 2002	Response Letter from NRC Staff to ACRS	ML023260357
September 29, 2003	Subcommittee Meeting	ML032940296*
March 3, 2005	Full Committee Meeting	ML050730030*
March 14, 2005	Letter from ACRS to NRC Chairman	ML050740211
April 25, 2005	Response Letter from NRC Staff to ACRS	ML050890012
July 27, 2005	Subcommittee Meeting	ML052230093*
September 8, 2005	Full Committee Meeting	ML052710235*
September 23, 2005	Letter from ACRS to NRC staff	ML052660300
November 3, 2005	Response Letter from NRC Staff to ACRS	ML052870363
November 1, 2006	Full Committee Meeting	ML063210302*
November 16, 2006	Letter from ACRS to NRC Chairman	ML063190465
January 19, 2007	Response Letter from NRC Staff to ACRS	ML070080254
January 19, 2007	Subcommittee Meeting	ML070390301*
February 2, 2007	Full Committee Meeting	ML070430485*
May 23, 2007	Letter from ACRS to NRC Chairman	ML071430639
July 11, 2007	Response Letter from NRC Staff to ACRS	ML071640115
December 2, 2008	Subcommittee Meeting	ML083530449*
December 4, 2008	Full Committee Meeting	ML083540616*
December 18, 2008	Letter from ACRS to NRC Chairman	ML083460310
January 23, 2009	Response Letter from NRC Staff to ACRS	ML083640532
May 10, 2011	Subcommittee Meeting	ML111450409*
June 8, 2011	Full Committee Meeting	ML11166A181*
June 22, 2011	Letter from ACRS to NRC staff	ML11164A048
June 23, 2011	Subcommittee Meeting	ML11193A035*

Date	Meeting/Letter	ADAMS Accession Number
July 13, 2011	Full Committee Meeting	ML11221A059*
July 21, 2011	Response Letter from NRC Staff to ACRS	ML111861706
December 15, 2011	Subcommittee Meeting	ML120100268*
January 19, 2012	Full Committee Meeting	ML12032A048*
January 26, 2012	Letter from ACRS to NRC Chairman	ML12023A089
February 17, 2012	Response Letter from NRC Staff to ACRS	ML120260893
November 7, 2013	Full Committee Meeting	ML13326A739*
November 21, 2013	Letter from ACRS to NRC Staff	ML13323B189
December 4, 2013	Subcommittee Meeting	ML13356A004*
November 3, 2015	Subcommittee Meeting	ML15320A187*
December 3, 2015	Full Committee Meeting	ML15349A717*

* Denotes transcript.

July 13, 2011	Full Committee Meeting	ML11221A059*
July 21, 2011	Response Letter from NRC Staff to ACRS	ML111861706
December 15, 2011	Subcommittee Meeting	ML120100268*
January 19, 2012	Full Committee Meeting	ML12032A048*
January 26, 2012	Letter from ACRS to NRC Chairman	ML12023A089
February 17, 2012	Response Letter from NRC Staff to ACRS	ML120260893
November 7, 2013	Full Committee Meeting	ML13326A739*
November 21, 2013	Letter from ACRS to NRC Staff	ML13323B189
December 4, 2013	Subcommittee Meeting	ML13356A004*
November 3, 2015	Subcommittee Meeting	ML15320A187*
December 3, 2015	Full Committee Meeting	ML15349A717*

* Denotes transcript.

Accession No: **ML16048A522** **Publicly Available** Y **Sensitive** N
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