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Secretary
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Attention: Rulemakings and Adjudications Staff

Docket: NRC-2008-0332

**Mark Edward Leyse's Comments on the Proposed Rule for Performance-Based
Emergency Core Cooling Systems Cladding Acceptance Criteria: 10 C.F.R. § 50.46(c)**

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In these comments, Mark Edward Leyse responds to the U.S. Nuclear Regulatory Commission’s (“NRC”) solicitation of public comments—published in the Federal Register on March 24, 2014—on a proposed rule, revising the acceptance criteria for the emergency core cooling system (“ECCS”) for light-water nuclear power reactors.

I. Statement of Commenter’s Interest

On March 15, 2007, Mark Edward Leyse submitted a 10 C.F.R. § 2.802 petition for rulemaking, PRM-50-84,¹ to NRC. PRM-50-84 requested that NRC make new regulations: 1) to require licensees to operate light water reactors under conditions that effectively limit the thickness of crud (corrosion products) and/or oxide layers on fuel cladding, in order to help ensure compliance with 10 C.F.R. § 50.46(b) ECCS acceptance criteria; and 2) to stipulate a maximum allowable percentage of hydrogen content in fuel cladding.

Additionally, PRM-50-84 requested that NRC amend Appendix K to Part 50—ECCS Evaluation Models I(A)(1), “The Initial Stored Energy in the Fuel,” to require that the steady-state temperature distribution and stored energy in the fuel at the onset of a postulated loss-of-coolant accident (“LOCA”) be calculated by factoring in the role that the thermal resistance of crud and/or oxide layers on cladding plays in increasing the stored energy in the fuel. PRM-50-84 also requested that these same requirements apply to any NRC-approved best-estimate ECCS evaluation models used in lieu of Appendix K to Part 50 calculations.

In 2008, NRC decided to consider the issues raised in PRM-50-84 in its rulemaking process.² And in 2009, NRC published “Performance-Based Emergency Core Cooling System Acceptance Criteria,” which gave advanced notice of a proposed rulemaking, addressing four objectives: the fourth being the issues raised in PRM-50-84.³ In 2012, the NRC Commissioners voted unanimously to approve a proposed rulemaking—revisions to Section 50.46(b), which will

¹ Mark Leyse, PRM-50-84, March 15, 2007 (ADAMS Accession No. ML070871368).

² Federal Register, Vol. 73, No. 228, “Mark Edward Leyse; Consideration of Petition in Rulemaking Process,” November 25, 2008, pp. 71564-71569.

³ Federal Register, Vol. 74, No. 155, “Performance-Based Emergency Core Cooling System Acceptance Criteria,” August 13, 2009, pp. 40765-40776.

become Section 50.46(c)—that was partly based on the safety issues Petitioner raised in PRM-50-84.⁴

Leyse also coauthored a paper, “Considering the Thermal Resistance of Crud in LOCA Analysis,”⁵ which was presented at the American Nuclear Society’s 2009 Winter Meeting.

II. Considering the Thermal Resistance of Crud and/or Oxide Layers in Loss-of-Coolant Accident Analysis

As published in SECY-12-0034, regarding the thermal effects of crud and oxide layers, the proposed rule for Section 50.46(c), Paragraph (g)(2)(ii), states:

The thermal effects of crud and oxide layers that accumulate on the fuel cladding during plant operation must be evaluated. For the purposes of this paragraph, crud means any foreign substance deposited on the surface of fuel cladding prior to initiation of a LOCA.⁶

Paragraph (g)(2)(ii) needs to be augmented with additional instructions, explaining that licensees are required to conservatively evaluate the thicknesses and thermal conductivities of crud and/or oxide layers for each fuel cycle.

Licensees will be better able to conservatively evaluate how the thermal effects of crud and oxide layers would increase the peak cladding temperature in the event of a LOCA, if they first conservatively evaluated the thicknesses and thermal conductivities of the crud and/or oxide layers present during each fuel cycle.

At the end of some fuel cycles, it would be helpful to examine the thicknesses and thermal conductivities of crud and oxide layers that had accumulated on fuel cladding; and estimate the quantity of non-tenacious crud released from fuel rods during the refueling outage. This would help to provide valid data for benchmarking ECCS evaluation models.

Clearly, there are a number of factors that could play a role in how much crud would be present in any forthcoming operating cycle. Ultrasonic fuel cleaning could be used to remove a portion of the existing crud; and of course more crud would accumulate on the fuel cladding.

⁴ NRC, Commission Voting Record, Decision Item: SECY-12-0034, Proposed Rulemaking—10 CFR 50.46(c): Emergency Core Cooling System Performance During Loss-of-Coolant Accidents (RIN 3150-AH42), January 7, 2013, (ADAMS Accession No. ML13008A368).

⁵ Rui Hu, Mujid S. Kazimi, Mark Leyse, “Considering the Thermal Resistance of Crud in LOCA Analysis,” American Nuclear Society, 2009 Winter Meeting, Washington, D.C., November 15-19, 2009.

⁶ NRC, “Proposed Rulemaking: 10 CFR 50.46c: Emergency Core Cooling System Performance During Loss-of-Coolant Accidents,” SECY-12-0034, March 1, 2012, p. 84.

But it's important to note that there are models of crud and oxide deposition that have been developed that are intended to predict of the thicknesses of crud deposits and oxide layers on the fuel cladding. (For example, such information is mentioned in a 2003 paper titled "Taming the Crud Problem: The Evolution."⁷)

In the question-and-answer session after a presentation I gave at NRC headquarters on June 24, 2014 regarding the Section 50.46c proposed rule, Paul Clifford made what I believe is an important point. He pointed out that during a fuel cycle there could be "fluffy," non-tenacious crud on the fuel rods, which would not be observed at the end of the fuel cycle. Non-tenacious crud can be released from fuel rods during refueling outages; this is sometimes termed a "crud burst." Regarding some observed crud bursts, Electric Power Research Institute ("EPRI") states that "[s]everal PWRs have experienced anomalous crud releases during refueling outages, characterized by unexpectedly high particulate crud releases followed by deposition or by abnormally high activity releases after peroxide addition (or release after floodup)."⁸

It is pertinent that EPRI has developed a BWR crud-deposition model called the Crud Deposition Risk Assessment Model ("CORAL"),⁹ "[t]o facilitate improved management of any crud-related fuel performance risk."¹⁰

Regarding CORAL, EPRI states:

The BWR Fuel Crud Model provides *a prediction of the crud deposition and tenacious crud layer thickness* both radially and axially within a selected fuel assembly throughout the entire operating history of the assembly. The analysis inputs include the fuel assembly geometry and actual or projected operating history, as well as crud inputs determined from a reactor system mass balance. A boiling deposition model, in conjunction with mechanistic crud release models, defines the deposited inventory along the length of all fuel rods within the fuel assembly. *The deposited crud material is separated between an outer loose, fluffy layer and an inner tenacious layer.* The thickness of the tenacious layer is determined [emphasis added].

⁷ Yovan D. Lukie, Jeffrey S. Schmidt, "Taming the Crud Problem: The Evolution," Advances in Nuclear Fuel Management 2003 Hilton Head Island, South Carolina, USA, October 2003.

⁸ EPRI, "Product Abstract: High Activity Crud Burst Impacts and Responses," available at: <http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=00000000001016766>

⁹ EPRI, "Product Abstract: Technical Basis and Benchmarking of the Crud Deposition Risk Assessment Model (CORAL)," available at: <http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?productId=00000000001025189>

¹⁰ EPRI, "Product Abstract: Fuel Reliability Program: BWR Fuel Crud Modeling," available at: <http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=00000000001021034>

The BWR Fuel Crud Model has been extensively validated through benchmarking of the model using data taken on fuel rods operated in actual commercial BWRs. These benchmarking measurements include (1) poolside fuel deposit sampling of *both total and tenacious crud layer*, (2) laboratory examination of crud flakes and tenacious deposits on irradiated fuel rods to determine composition, thickness, density, and structure, and (3) poolside eddy current lift-off and cladding diametral profilometry data. This successful benchmarking activity provides confidence in the model's ability to capture and quantitatively describe crud deposition behavior, as well as quantifying the inherent variability in the crud deposition and release processes and resultant tenacious crud layer thickness¹¹ [emphasis added].

Such models need to be used to predict the thicknesses of crud deposits—for both outer loose, fluffy layers and inner tenacious layers—that would be present on the fuel cladding during each fuel cycle. And such models need to be used for both PWRs and BWRs. Clearly, the thermal effects of crud—for fluffy layers and tenacious layers—and oxide layers need to be evaluated in LOCA analysis; and the thicknesses and thermal conductivities of such layers need to be modeled conservatively.

III. Results of the PHEBUS B9R-2 Test Pertain to How Breakaway Oxidation Could Affect a LOCA

As published in SECY-12-0034, the proposed rule for Section 50.46(c) states:

Breakaway oxidation, for zirconium-alloy cladding material, means the fuel cladding oxidation phenomenon in which weight gain rate deviates from normal kinetics. This change occurs with a rapid increase of hydrogen pickup during prolonged exposure to a high-temperature steam environment, which promotes loss of cladding ductility.¹²

And Draft Regulatory Guide 1261 states that “breakaway oxidation is an instability phenomenon that can spread rapidly in the axial and circumferential directions” of fuel rods and that there is a criterion of 200-weight parts per million (wppm) for hydrogen pickup. It says that

¹¹ *Id.*

¹² NRC, “Proposed Rulemaking: 10 CFR 50.46c: Emergency Core Cooling System Performance During Loss-of-Coolant Accidents,” SECY-12-0034, March 1, 2012, p. 78.

fuel-cladding ductility is maintained as long as the average hydrogen content is below 435 wppm.¹³

Draft Regulatory Guide 1261 states:

[T]he 200-wppm hydrogen pickup criterion is conservative by a factor of at least two. However, it is not overly conservative for high oxidation temperatures because the time needed to increase from 200 wppm to >400 wppm hydrogen pickup could be as low as 100 seconds.¹⁴

When high burnup and other fuel rods are discharged from the reactor core, the fuel cladding can have local zirconium dioxide (ZrO_2) “oxide” layers that are up to 100 microns (μm) thick (or greater); there can also be local crud layers on top of the oxide layers. And according to NUREG/CR-6851, medium to high burnup fuel cladding typically has a “hydrogen concentration in the range of 100-1000 wppm;” it adds that “[z]irconium-based alloys, in general, have a strong affinity for oxygen, nitrogen, and hydrogen...”¹⁵

NRC’s conclusions on how hydrogen content affects fuel cladding ductility are based on the results of isothermal experiments conducted with small specimens. These were experiments in which a tiny section of a fuel rod was held at a constant temperature. I think most of this program was done at Argonne; and there were some tests done with pre-oxidized fuel cladding.

The PHEBUS B9R-2 test is an integral experiment conducted with pre-oxidized fuel cladding, which I recommend the NRC study. PHEBUS B9R-2 was conducted in a light water reactor—as part of the PHEBUS severe fuel damage program—with an assembly of 21 UO_2 fuel rods.¹⁶ A 1996 European Commission report states that the B9R-2 test had an unexpected fuel-cladding temperature escalation in the mid-bundle region; the highest temperature escalation rates were from 20°C/sec (36°F/sec) to 30°C/sec (54°F/sec).¹⁷

¹³ NRC, “Conducting Periodic Testing for Breakaway Oxidation Behavior,” Draft Regulatory Guide 1261, Undated, Appendix B: Rational for the 200-wppm Hydrogen Pickup Criterion for Breakaway Oxidation,” (ADAMS Accession No: ML111100300), p. B-1.

¹⁴ *Id.*

¹⁵ K. Natesan, W.K. Soppet, Argonne National Laboratory, “Hydrogen Effects on Air Oxidation of Zirlo Alloy,” NUREG/CR-6851, October 2004, (ADAMS Accession No: ML042870061), p. iii, 3.

¹⁶ G. Hache, R. Gonzalez, B. Adroguer, Institute for Protection and Nuclear Safety, “Status of ICARE Code Development and Assessment,” in NRC “Proceedings of the Twentieth Water Reactor Safety Information Meeting,” NUREG/CP-0126, Vol. 2, 1992, (ADAMS Accession No: ML042230126), p. 311.

¹⁷ T.J. Haste *et al.*, “In-Vessel Core Degradation in LWR Severe Accidents,” European Commission, Report EUR 16695 EN, 1996, p. 33.

Discussing PHEBUS B9R-2, the 1996 European Commission report states:

The B9R-2 test...illustrates the oxidation in different cladding conditions representative of a pre-oxidized and fractured state. ... During B9R-2, an unexpected strong escalation of the oxidation of the remaining Zr occurred when the bundle flow injection was switched from helium to steam while the maximum clad temperature was equal to 1300 K [1027°C (1880°F)]. The current oxidation model was not able to predict the strong heat-up rate observed even taking into account the measured large clad deformation and the double-sided oxidation (final state of the cladding from macro-photographs).

... No mechanistic model is currently available to account for enhanced oxidation of pre-oxidized and cracked cladding.¹⁸

As stated, the cladding-temperature escalation commenced at approximately 1027°C (1880°F). That is thermal runaway. The fact that PHEBUS B9R-2 was conducted with a preoxidized test bundle makes its results pertinent to the cladding of medium and high burnup fuel rods.

The hydrogen content of the cladding of PHEBUS B9R-2 test bundle most likely played a role in the test results. I think the results indicate what could happen in a LOCA; the test was conducted under conditions far more representative of LOCA conditions than the Argonne tests with tiny specimens.

As quoted above, Draft Regulatory Guide 1261 states that breakaway oxidation deviates from normal kinetics. It seems that normal oxidation kinetics are supposed to be those observed in the tests with tiny zirconium specimens held at a constant temperature. In such tests the rate of steam flow is controlled. And different adjustments can influence oxidation rates. This is discussed in a paper by Gerhard Schanz titled “Recommendations and Supporting Information on the Choice of Zirconium Oxidation Models in Severe Accident Codes.” The Schanz paper states that an investigator “reached an important improvement of the specimen temperature homogeneity by only optimizing the geometry of the specimen and registered considerably increased reaction rates.”¹⁹

I think that any honest, objective study of the results of the PHEBUS B9R-2 test and those of a number of other integral experiments conducted with multi-rod bundles of fuel rod simulators or real fuel rods with UO₂ fuel would reveal many deviations from so-called normal

¹⁸ *Id.*, p. 126.

¹⁹ Gerhard Schanz, “Recommendations and Supporting Information on the Choice of Zirconium Oxidation Models in Severe Accident Codes,” FZKA 6827, 2003, p. 5.

oxidation kinetics. The reaction rates have been rapid in a number of the large-scale, integral experiments. In those cases thermal runaway is more of an issue than cladding embrittlement. Preventing thermal runaway could be a more important safety issue than preventing excessive cladding embrittlement.

IV. Results of the PHEBUS B9R-2 Test Pertain to the 2200°F Peak Cladding Temperature Limit

The results of the PHEBUS B9R-2 test should be reviewed, along with other integral experiments to help determine if the proposed rule for Section 50.46(c), Paragraph (g)(1)(i) is non-conservative. That is, the test results of integral experiments may indicate that the 2200°F peak cladding temperature limit needs to be lowered. In a large break LOCA there could be steam-binding conditions that would not allow much coolant to be injected. This could cause the fuel-cladding temperature to increase at a rate of approximately 10°F per second or greater—mainly from the stored energy (heat) in the fuel, at the beginning of the LOCA. And if the peak fuel-cladding temperature were to reach approximately 1832°F in a steam environment; and there were little or no coolant injection, there would probably be results similar to those of the PHEBUS B9R-2 test, in which thermal runaway commenced when peak fuel-cladding temperatures were lower than 2200°F.

Respectfully submitted,

/s/

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