PRM-50-84

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

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OFFICE OF SECRETARY
RULEMAKINGS AND
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PETITION FOR RULE MAKING

I. BRIEF DESCRIPTION OF NEEDED REGULATIONS

This petition for rulemaking is submitted pursuant to 10 C.F.R. § 2.802 by Mark Edward Leyse. Petitioner requests that the United States Nuclear Regulatory Commission ("NRC") require all holders of operating licenses for nuclear power plants to operate such plants at operating conditions (*e.g.*, levels of power production, fuel-cycle lengths, and light-water coolant chemistries) necessary to effectively limit the thickness of crud (corrosion products) layers on fuel rods ("cladding") and/or the thickness of oxide layers on cladding surfaces. New regulations are needed for reactor-operation parameters, uranium-oxide and mixed-oxide fuel, and cladding, in order to ensure that cladding is free of unsafe thicknesses of crud and/or oxide, which in turn would help ensure that nuclear power plants operate in compliance with 10 C.F.R. § 50.46(b). Among other requirements, 10 C.F.R. § 50.46(b) stipulates that the calculated peak cladding temperature ("PCT") must not exceed 2200°F in the event of a loss-of-coolant accident ("LOCA").

Petitioner also requests that the 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 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. Appendix K should also provide instructions for how to carry out calculations that factor in the role that the thermal resistance of crud and/or oxide layers on cladding plays in determining the quantity of stored energy in the fuel at the onset of a postulated LOCA.

These requirements also need to apply to any NRC approved best-estimate ECCS evaluation models used in lieu of Appendix K calculations.[1]

Additionally, Petitioner requests that the NRC amend 10 C.F.R. § 50.46, *Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors*, to include a regulation stipulating a maximum allowable percentage of hydrogen content in cladding. These requirements also need to apply to any NRC approved best-estimate ECCS evaluation models used in lieu of Appendix K calculations.

II. STATEMENT OF PETITIONER'S INTEREST

Petitioner is aware that layers of crud and/or oxide on cladding surfaces cause the temperature of fuel rods to increase during the operation of nuclear power plants (sometimes in excess of 300°F or even 600°F).[2] The low thermal conductivity of crud and/or oxide inhibits heat transfer, causing cladding temperatures to increase; temperatures also increase in the fuel sheathed within the cladding (*i.e.*, the stored energy in the fuel increases). In the event of a LOCA, the thermal resistance of insulating layers of crud and/or oxide on cladding, and increased fuel temperatures, will cause the PCT to be higher than it would be if the cladding were clean. If a large break ("LB") LOCA had occurred in recent years at several nuclear power plants that operated with heavy crud and oxide layers, there is a high probability that their PCTs would have exceeded 2200°F.

Additionally, hydriding of cladding—like oxidation of cladding—contributes to cladding embrittlement. 10 C.F.R. § 50.46 needs to be updated to include a regulation stipulating a maximum allowable percentage of hydrogen in cladding; the 1973 Rule-

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[1] NRC, "10 CFR Part 50: Risk-Informed Changes to Loss-of-Coolant Accident Technical Requirements," 2005, located at: http://www.nrc.gov/reading-rm/doc-collections/commission/secys/2005/secy2005-0052/2005-0052scy.pdf (accessed on 01/21/07), p. 11. Best-estimate ECCS evaluation models used in lieu of Appendix K calculations are described in NRC Regulatory Guide 1.157.

[2] NRC, "River Bend Station – NRC Problem Identification and Resolution Inspection Report 0500458/2005008," 02/28/06, Report Details, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML060600503, p.10.

Making Hearing of the U.S. Atomic Energy Commission took place before there was extensive knowledge of the effect of hydriding on cladding embrittlement.[3]

III. BACKGROUND

A. The Thermal Resistance Effects of Crud and/or Oxide Layers on Cladding.

The thermal resistance of crud and/or oxide layers on cladding causes cladding and uranium oxide fuel temperatures to increase (sometimes in excess of 300°F or even 600°F in the case of cladding)[4] during the operation of nuclear power plants. In the event of a LB LOCA, there is a high probability that the insulating effects of crud and oxide, and increased fuel temperatures (caused by crud and oxide) would result in the PCT of any plant with heavy layers of crud and oxide exceeding 2200°F, in violation of 10 C.F.R. § 50.46(b)(1), *Peak cladding temperature*. 10 C.F.R. § 50.46(b)(1) states: "[t]he calculated maximum fuel element cladding temperature shall not exceed 2200°F."

In 2001, Indian Point Unit 2 had a peak cladding temperature (PCT) of 2188°F in a computer simulated LB LOCA—only 12°F shy the requirements of 10 C.F.R. § 50.46(b)(1)).[5] If there had been heavy crud and oxide layers on the cladding at Indian Point Unit 2 in 2001, it is highly probable that the calculated PCT would have exceeded 2200°F, perhaps by hundreds of degrees Fahrenheit, in a computer simulation of a LB LOCA (if the thermal resistance of such layers were taken into account in the calculation).

When a computer simulated LB LOCA for a nuclear power plant calculates its PCT at 2188°F there is much cause for concern. It means that if it experienced a real-life LB LOCA and had unsafe thicknesses of crud and oxide on cladding there is a high probability that the PCT would exceed 2200°F. In real life, surpassing a cladding temperature of 2200°F could cause cladding to lose its physical integrity and lead to a

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[3] Nuclear Energy Agency, Committee on the Safety of Nuclear Installations, Special Expert Group on Fuel Safety Margins, Summary Record of the Topical Meeting on LOCA Fuel Safety Criteria and the Second SEG FSM Meeting, March 22-23, 2001, p. 6.

[4] NRC, "River Bend Station – NRC Problem Identification and Resolution Inspection Report 0500458/2005008," Report Details, p.10.

[5] Consolidated Edison Company of New York, Inc., "Indian Point Unit 2 – 30 Day and Annual 10 CFR 50.46 Report," April 10, 2001, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML011150434.

core meltdown. In a worst-case scenario a core meltdown would breach the containment vessel of a reactor and release radioactive material and contaminate the environment. Such a catastrophic accident would cause immense human suffering and economic damage, and render large areas of land uninhabitable.

1. Crud-Induced Cladding Corrosion Failures at Three Mile Island Unit 1 Cycle 10.

In 1995, Three Mile Island Unit 1 ("TMI-1"), a pressurized water reactor ("PWR"), operated with crud deposits on the surface of fuel rods that caused regions of the cladding to be "subjected to temperatures in the range 450 to 500°C or greater."[6] Under typical operating conditions at TMI-1, the maximum cladding temperature is 346°C,[7] meaning that crud deposits raised the cladding temperature by over 100 or 150°C (180 or 270°F) or greater. This illustrates that it is highly probable that Indian Point Unit 2 would have had a PCT over 2200°F in its computer simulated LB LOCA if it had had cladding conditions similar to those of TMI-1 Cycle 10. It is also highly probable that if a real-life LB LOCA had occurred at TMI-1 during a significant period of cycle 10, the heavy crud and oxide layers on the cladding would have caused the PCT to exceed 2200°F.

Discussing crud and its effect on increasing cladding temperature, the paper "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10"[8] states:

> The cause of the higher temperature on the outer face of the peripheral rods is believed to result from local deposition of a crud layer, which impeded heat transfer. Steam blanketing within a layer of dense crud could significantly increase local temperatures, and it has been implicated in past fuel failures in low duty PWRs, and more recently in failures in higher duty plants. The effect of steam blanketing would be similar to a dryout, both would preclude water to effectively remove heat from the fuel rod surface, causing the fuel rod to over-heat.[9]

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[6] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," American Nuclear Society, Proceedings of the *2004 International Meeting on LWR Fuel Performance*, Orlando, Florida, September 19-22, 2004, p. 342.

[7] *World Nuclear Industry Handbook, 1995*, Nuclear Engineering International (England), p. 80.

[8] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," pp. 339-347.

[9] Id., p. 343.

At TMI-1 Cycle 10, the first leaking rod (a symptom of a cladding perforation) was detected 121 days into the cycle. When cladding is perforated by corrosion, increases in offgas activity are detected in the coolant. Different steps can be taken: the power can be suppressed at the assemblies where leaking rods are detected or the fuel cycle can be terminated in order to remove the failed fuel rods. But because corrosion is not detected during plant operation, there is often a significant length of time before corrosion progresses and perforates cladding and causes an increase in offgas activity, meaning that heavily corroded fuel rods are often operated at full power for significant periods of time. It is hypothesized that at TMI-1 Cycle 10 cladding temperatures of a range of 450 to 500°C or greater lasted "for an indeterminate time, but within the range of ~1000 to 10 hours for the respective temperature limits."[10]

In 1995, TMI-1 had PWR Zr-4 fuel-rod cladding with a thickness of .67 mm or 670 μm (microns).[11] After cycle 10, 38 fuel assemblies were observed with a Distinctive Crud Pattern ("a mottled appearance of a dark, nearly black surface with jagged patches of white showing through").[12] Additionally, after cycle 10, the maximum oxide thickness measured on a fuel rod was 111.1 μm, at an axial elevation of 118.5 inches.[13] Therefore, the equivalent cladding reacted ("ECR"); that is, the percentage of the cladding of that rod that had oxidized, was 10.6% (this percentage is calculated by dividing the oxide thickness (111.1 μm) by the oxide to metal ratio of 1.56[14] (the value 1.56 is derived from the atomic weights of the elements involved in the chemical reaction of oxygen and Zircaloy cladding) and then dividing that value (71.2 μm) by the cladding thickness (670 μm)).

It is pertinent that, "Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel," from 2000, states, "[r]ecent out-of-reactor measured elastic and plastic cladding strain values from high burnup cladding from two PWR fuel vendors

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[10] Id., p. 342.

[11] *World Nuclear Industry Handbook 1995*, p. 80.

[12] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 340.

[13] Id., p. 344.

[14] NRC, Advisory Committee on Reactor Safeguards, Materials, Metallurgy, and Reactor Fuels Subcommittee Meeting Transcript, January 19, 2007, located at: http://www.nrc.gov/reading-rm/doc-collections/acrs/tr/subcommittee/2007/mm011907.pdf (accessed on 02/27/07), p. 243.

have shown a decrease in Zr-4 cladding ductilities when oxide thicknesses begin to exceed 100 μm. As a result, the NRC staff has encouraged fuel vendors to establish a maximum oxide thickness limit of 100 μm."[15] (This is a NRC recommendation for guidance; it is not a legally binding regulation.) (It is also interesting, that the TMI-1 Cycle 10 cladding—because of the low thermal conductivity of the crud layer—had an oxide thickness measured at over 100 μm (on one-cycle cladding), and that one-cycle cladding was initially perforated by oxidation only 121 days into the cycle.)

"NRC Information Notice 98-29: Predicted Increase in Fuel Rod Cladding Oxidation" states that the "[t]otal oxidation [of cladding] includes both pre-accident oxidation and oxidation occurring during a LOCA."[16] This NRC information notice applies to CFR § 10 50.46(b)(2), *Maximum cladding oxidation*, which dictates the rule for the maximum allowed value of the ECR (equivalent cladding reacted) calculated by severe accident analysis programs (codes) when simulating LOCAs. It states: "[t]he calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation." Concerning this 17% limit NRC Information Notice 98-29 warns: "[i]f this...oxidation limit [of 17%] were to be exceeded during an accident, the cladding could become embrittled. The cladding could then fracture and fragment during the reflood period and lose structural integrity. This in turn could compromise the structural soundness and coolable geometry of the core and ultimately the ability to keep the core cooled."[17]

If there had been a LOCA at TMI-1 Cycle 10, it is highly probable that the ECR, at the location where oxide thickness was measured at 111.1 μm, would have increased from a pre-accident value of 10.6% to a during-accident value exceeding 17%. Petitioner's point, however, is not to make an issue out of this supposition about the

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[15] David B. Mitchell and Bert M. Dunn, "Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel," February 2000, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML003686365, p. xviii.

[16] NRC, "NRC Information Notice 98-29: Predicted Increase in Fuel Rod Cladding Oxidation," August 3, 1998, located at: http://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/1998/in98029.html (accessed on 01/21/07).

[17] Id.

ECR; after all, during cycle 10, fuel rods had failed due to local corrosion penetration,[18] and at the cladding perforations the ECR was already 100%. The point is rather to focus on the role that the thermal resistance of heavy layers of oxide and crud on cladding would play during a LOCA.

The maximum observed crud thickness from TMI-1 Cycle 10 was measured at 33 μm.[19] However, the analysis of the crud deposits on the cladding conducted after cycle 10 could not be thorough because most of the crud samples that had been collected disappeared into a storage pool, with a pH of about 4.5, before they were examined.[20] Typically, a great deal of PWR crud comes off the cladding during reactor shutdown: as much as four kilograms of crud can depart from cladding surfaces during reactor shutdown. Hence, the thickness of the crud that deposits on the cladding during plant operation is often unknown.[21] Thus, in the case of TMI-1 Cycle 10, the crud thicknesses were almost certainly much thicker than the values measured; perhaps they were 100 μm or greater. In fact, crud deposits on cladding in PWRs have been measured at up to 125 μm thick.[22]

a. The Thermal Conductivities of Crud and Zirconium Dioxide.

As already mentioned, the crud layer increased the cladding surface temperature by over 180 or 270°F or greater during cycle 10 because the thermal conductivity of the crud layer was very low. Pertaining to the thermal conductivity of crud is a citation from the transcript of proceedings from the NRC's Advisory Committee on Reactor Safeguards ("ACRS"), Reactor Fuels Subcommittee, September 30, 2003:

> [T]he thermal conductivity of the crud all depends on the morphology more than from the type, the chemical composition because the crud, say, it comes as a solid, the solid iron oxide conductivity is better than zirconium by maybe a factor of two to five. ... If the morphology is such that it would cause a steam blanketing, then your steam has extremely

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[18] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 343.
[19] Id., p. 340.
[20] NRC, Advisory Committee on Reactor Safeguards, Reactor Fuels Subcommittee Meeting Transcript, September 30, 2003, located at: http://www.nrc.gov/reading-rm/doc-collections/acrs/tr/subcommittee/2003/rf093003.pdf (accessed on 01/21/07), p. 241.
[21] Id., pp. 241-242.
[22] Id., p. 133.

> poor conductivity, maybe two orders of magnitude lower than the... The crud is so difficult to characterize. And the conductivities all so much depend on the morphology.[23]

The thermal conductivity of crud is reported to be 0.8648 W/mK in volume two of the code manual, "Frapcon-3: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup."[24] This same value for the thermal conductivity of crud is given in NUREG-1230, dating back to 1988.[25] So it is evident that—although 0.8648 W/mK is a very low thermal conductivity—the speaker at the Reactor Fuels Subcommittee, on September 30, 2003, thought a crud layer with steam blanketing would have an even lower thermal conductivity than 0.8648 W/mK. He stated that steam trapped within a crud layer (with steam blanketing) would have "extremely poor conductivity." This is because the thermal conductivity of steam is extremely low: it has been measured between values of 0.0154 and 0.0678 Btu/hrftF (0.0267 and 0.1173 W/mK) between temperatures of 250 and 1500°F (394.26 and 1088.7°K) and pressures of 20 and 2000 psia.[26] He also stated that "crud is...difficult to characterize" and that its thermal "conductivities...depend on [its] morpholog[ies]." (For example, a ~100 μm crud flake, from a boiling water reactor ("BWR") that experienced crud-induced fuel failures, has been described as having a 50% porosity with voids and plugged up steam chimneys.[27]) So it is clear that certain morphologies of crud have thermal conductivities that are less than 0.8648 W/mK and of unknown values.

In fact, Electric Power Research Institute ("EPRI") currently (to be completed in 2008) has a goal to "[p]erform crud simulation tests to determine the effect of tenacious

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[23] Id., p. 240.

[24] Pacific Northwest National Laboratory, NUREG/CR-6534, Volume 2, "Frapcon-3: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup," 1997, p. 2.8.

[25] NRC, NUREG-1230, "Compendium of ECCS Research for Realistic LOCA Analysis," 1988, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML053490333, p. 6.14-4.

[26] C. A. Meyer, R. B. McClintock, G. J. Silvestri, R. C. Spencer, Jr., ASME Steam Tables, The American Society of Mechanical Engineers, 1983, p. 281.

[27] Rosa Yang, Odelli Ozer, Kurt Edsinger, Bo Cheng, Jeff Deshon, "An Integrated Approach to Maximizing Fuel Reliability," American Nuclear Society, Proceedings of the *2004 International Meeting on LWR Fuel Performance*, Orlando, Florida, September 19-22, 2004, p. 14.

crud on fuel surface heat transfer."[28] This study is for BWR crud but its results could also be applied to PWRs. As the article "Fuel Formation and Behavior," describing a project for sampling BWR crud flakes, claims: "methods developed to determine the number and distribution of chimneys and capillaries on fuel crud surface, essential in understanding the adequacy of heat transfer within...crud deposit[s] have large applications for both PWR and BWR fuel depositions."[29] Whether or not the findings of this research will be applied to modeling crud for calculations of PCTs during postulated LOCAs is open to conjecture.

Zirconium dioxide (ZrO_2) or zirconia also has a low thermal conductivity, and is used industrially as an insulating material.[30] The thermal conductivity of zircaloy-cladding oxide has been measured between 1.354 and 1.586 W/mK at temperatures between 297 and 1450°K, dipping as low as 0.955 W/mK at 668°K.[31] Additionally, volume one of the code manual, "Frapcon-3" (published in 1997) states that the current MATPRO function for ZrO_2, uses values of approximately 2.0 W/mK for the thermal conductivity of ZrO_2 at typical LWR operating cladding temperatures. But it also states that in 1995 an EPRI-sponsored Halden Reactor experiment gave indications that the value for the thermal conductivity of ZrO_2 at the same temperatures may be much lower, at values close to 1.0 W/mK.[32] Like crud, oxide also impedes heat transfer:

> Crud inhibits heat transfer, increasing clad temperature and oxide layer growth rate. ... Oxide can form, with or without the benefit of crud, in the presence of sustained elevated cladding temperatures. Like crud,

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[28] EPRI, "2007 Portfolio, AP41.02 Fuel Reliability," located at: http://mydocs.epri.com/docs/Portfolio/PDF/2007_P041-002.pdf (accessed on 01/21/07), p. 5.

[29] Charles Turk, "Fuel Crud Formation and Behavior," *Nuclear Plant Journal*, January-February 2006, located at: http://npj.goinfo.com/NPJMain.nsf/504ca249c786e20f85256284006da7ab/89609e291af0b7b286257194007576c1?OpenDocument (accessed on 01/21/07).

[30] The following is from a description of the "Hot Spot 110: 1700°C Lab Furnace": "The zirconia insulation incorporated in the Hot Spot 110 has the lowest thermal conductivity of any commercially available high temperature insulation," located at: http://www.zircarzirconia.com/doc/F-HS.pdf (accessed on 01/21/07).

[31] K. E. Gilchrist, "Thermal Property Measurements on Zircaloy-2 and Associated Oxide Layers," *Journal of Nuclear Materials*, 62, 1976, pp. 257-264.

[32] Pacific Northwest National Laboratory, NUREG/CR-6534, Volume 1, "Frapcon-3: Modifications to Fuel Rod Material Properties and Performance Models for High-Burnup Application," 1997, p. 8.3.

> formation of an oxide layer inhibits heat transfer causing accelerated corrosion which can potentially lead to fuel failure.[33]

b. A Discussion of an Individual Fuel Rod at TMI-1 Cycle 10.

Fuel rod (rod 011) was one of the fuel rods that failed at TMI-1 Cycle 10. As already mentioned, the maximum oxide thickness measured on rod 011 was 111.1 μm, and elsewhere on the same rod oxidation had perforated the cladding. There is a high probability that during cycle 10, on rod 011 there had been a crud layer that was approximately 100 μm thick on top of the 111.1 μm oxide layer. Such a crud layer would have been the primary cause of the 111.1 μm oxide layer, as well as the perforations on rod 011. Therefore, it is highly probable that rod 011 had an approximately 200 μm layer of oxide and crud combined; that is, a heavy layer with a very low thermal conductivity (with plausible values of approximately 1.4 W/mK or less for the oxide portion of the layer and a value less than 0.8648 W/mK—most likely, substantially less—for the crud portion).

If a LB LOCA had occurred at TMI-1 Cycle 10, the very low thermal conductivity of the 200 μm layer of oxide and crud combined would have inhibited effective heat transfer and with high probability caused the PCT to exceed 2200°F (~1204°C), in violation of 10 C.F.R. § 50.46(b)(1), which in turn could have caused a meltdown.

The 111.1 μm oxide layer and the crud layer of a possible thickness of approximately 100 μm were on rod 011 at an elevation 118.5 inches above the bottom of the end plug, or about 80% above the base of the active core.[34] At TMI-1 Cycle 10 the crud layer was observed to be heaviest in fuel-rod span six, which "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10" states, was "the hottest span" of the fuel assemblies during cycle 10. Crud was also observed in spans five and seven[35] or at

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[33] Yovan D. Lukic and Jeffery S. Schmidt, "Taming the Crud Problem: The Evolution," *Advances in Nuclear Fuel Management III Conference*, Hilton Head Island, South Carolina, October 2003.

[34] *World Nuclear Industry Handbook 1995*, p. 80. At Three Mile Island during cycle 10 the active core height was 3.6 meters or 143.9 inches.

[35] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 340.

elevations from around 80 to 120 inches above the bottom of the end plug[36] (around 55 to 80% above the base of the active core). Typically, during a postulated LOCA the PCT occurs approximately 60% above the base of the active core. Therefore, for clean cladding at TMI-1, during a postulated LOCA, it seems highly probable that at an elevation of 118.5 inches, the temperature would have been calculated within 100°F of the PCT. (Of course, this is a simple assessment: the phenomena occurring during a LOCA are very complex; the actual elevation of the PCT for clean cladding at TMI-1, around 1995, can be researched, as well as what the temperature would have been at the 118.5 inch elevation for clean cladding.) Therefore, it is still highly probable that the cladding temperature would have exceeded 2200°F during a postulated LB LOCA at the 118.5 inch elevation on rod 011, as well as on other fuel rods at the span-six elevations, during cycle 10.

As stated before, in 2001, Indian Point Unit 2 had a PCT of 2188°F in a computer simulated LB LOCA—only 12°F shy the requirements of 10 C.F.R. § 50.46(b)(1)).[37] If Indian Point Unit 2 had cladding conditions similar to those of TMI-1 Cycle 10 there is a high probability that its PCT would have exceeded 2200°F in the event of a LB LOCA, because during cycle 10 cladding temperatures were raised over 180 or 270°F or even greater by layers of crud and oxide.

TMI-1 is not the only PWR to experience crud-induced corrosion failures in recent years in the United States: Palo Verde Unit 2 (cycle 9, 2000)—which, in 1997, during a postulated LB LOCA, had a PCT somewhere between 2143 and 2165°F[38]—and Seabrook (cycle 5, 1997) had the same problem. (Most of the fuel rods that experienced crud-induced corrosion failure in these three cases were high-power, one-cycle rods.[39])

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[36] Id., p. 344.

[37] Consolidated Edison Company of New York, Inc., "Indian Point Unit 2 – 30 Day and Annual 10 CFR 50.46 Report," April 10, 2001, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML011150434.

[38] See Secy-97-200, "Weekly Information Report – Week Ending August 29, 1997," 09/04/97, located at: http://www.nrc.gov/reading-rm/doc-collections/commission/secys/1997/secy1997-200/1997-200scy.pdf (accessed on 01/21/07); see also "Part 21 Report: 1997-56-1," 08/14/97, located at: http://www.nrc.gov/reading-rm/doc-collections/event-status/part21/1997/1997561.html (accessed on 01/21/07).

[39] NRC, Advisory Committee on Reactor Safeguards, Reactor Fuels Subcommittee Meeting Transcript, September 30, 2003, p. 235.

And at an unidentified PWR crud-induced corrosion was responsible for "a delaminated and spalling oxide of up to 200μm [thick]."[40]

2. The Stored Energy in Fuel Sheathed within Crudded and Oxidized Cladding.

When cladding temperatures are increased by layers of crud and oxide, there is also an increase in the stored energy in the fuel, because the thermal resistance of insulating layers of crud and oxide increase fuel temperatures. Describing how the quantity of stored energy in the fuel is partly related to heat transfer through cladding NUREG-1230, "Compendium of ECCS Research for Realistic LOCA Analysis," states:

> The amount of stored energy [in the fuel] is directly related to the temperature of the fuel center and the temperature gradient from the fuel center to the fuel surface. The temperature of the fuel center and the temperature gradient are a function of thermal conduction within the pellet, fuel pellet cracking, heat transfer through the fuel cladding gap, *and conduction through the cladding* [emphasis added].[41]

Because crud and/or oxide layers impede heat conduction through cladding, the stored energy in the fuel increases when the cladding encasing it is heavily crudded and/or oxidized. And the stored energy in the fuel at the onset of a LOCA is significant for determining the PCT during a LOCA; "Compendium of ECCS Research for Realistic LOCA Analysis," states, "[d]uring the blowdown period, fuel and cladding temperatures are in part determined by the initial stored thermal energy in the fuel rods."[42]

Concerning the effect that fuel temperatures (or stored energy), at the onset of a LOCA, have on the PCT (during a postulated LOCA), the NRC, discussing Westinghouse's PAD 4.0 code, states:

> The PAD 4.0 code is used to provide initial thermal conditions (fuel centerline and volume average temperatures) and rod pressures for the start of the LOCA analysis. The fuel volume average temperature is the *primary* PAD input that impacts the calculation of maximum peak cladding temperatures (PCTs) to verify that Westinghouse meets the 10

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[40] Bo Cheng, David Smith, Ed Armstrong, Ken Turnage, Gordon Bond, "Water Chemistry and Fuel Performance in LWRs," American Nuclear Society, Proceedings of the *2000 International Meeting on LWR Fuel Performance*, Park City, Utah, April 10-13, 2000.

[41] NRC, NUREG-1230, "Compendium of ECCS Research for Realistic LOCA Analysis," p. 6.14-2.

[42] Id., p. 6.14-1.

> CFR 50.46 requirement of PCT not exceeding 2200°F. Traditionally, the NRC has required that a best estimate code such as PAD 4.0 maintain a 95 percent bounding estimate of centerline and volume average temperatures at a 95 percent confidence level for input to LOCA analysis. ... From the example LOCA calculation provided by Westinghouse, the *maximum* fuel temperatures (generally corresponds to *maximum* PCTs) calculated by PAD 4.0 are consistent with the FRAPCON-3 code results [emphasis added].[43]

Furthermore, concerning stored energy in the fuel at the onset of a LOCA, "Compendium of ECCS Research for Realistic LOCA Analysis" states:

> The amount of stored energy in the fuel at the start of a reactor transient plays an important role in the response of the fuel rod during the transient. A portion of the stored energy (typically more than 50%) is removed during the blowdown period of LOCA. The residual thermal energy is in the fuel rod at the beginning of the adiabatic heatup phase of the LOCA. The amount of residual thermal energy influences the time required to quench the reactor core with emergency cooling water.[44]

And to clarify how a heavy crud layer would affect the stored energy in the fuel during a LOCA is a citation from a letter from James F. Klapproth, Manager, Engineering and Technology at GE Nuclear Energy, to the NRC:

> The primary effects of [a] heavy crud layer during a postulated LOCA would be an increase in the fuel stored energy at the onset of the event, and a delay in the transfer of that stored energy to the coolant during the blowdown phase of the event.[45]

The fact that a heavy crud layer would: 1) increase the stored energy in the fuel at the onset of a LOCA; and 2) delay the transfer of that stored energy to the coolant during the blowdown phase of a LOCA, is very significant for how cladding would be affected during a LOCA.

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[43] NRC, "Safety Evaluation by the Office of Nuclear Reactor Regulation, Topical Report WCAP-15063-P, Revision 1, 'Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)'," April 24, 2000, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML003706392, pp. 7-8.

[44] NRC, NUREG-1230, "Compendium of ECCS Research for Realistic LOCA Analysis," p. 6-14-2.

[45] Letter from James F. Klapproth, Manager, Engineering and Technology, GE Nuclear Energy to Annette L. Vietti-Cook, Secretary of the Commission, NRC, April 8, 2002, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML021020383.

The increase of the stored energy in the fuel caused by a heavy crud layer is substantial (in some cases, enough to increase cladding temperatures in excess of 300°F or even 600°F during operation).[46] This increase raises the stored energy in the fuel to levels higher than that of fresh, beginning-of-life ("BOL") fuel, or fuel with burnups between 30 to 35 GWd/MTU, which are considered the times of life or burnups that represent the maximum stored energy that fuel has during operation. (Fresh, BOL fuel is generally considered to have the maximum stored energy in fuel; however, COPERNIC and FRAPCON-3 (computer codes, programs that simulate LOCAs) calculate that mid-life fuel with burnups of about 30 to 35 GWd/MTU have the maximum stored energy.)[47] The values of the stored energy in BOL fuel or fuel with burnups between 30 to 35 GWd/MTU are what are used to calculate PCTs during postulated LOCAs by computer codes because the maximum stored energy in the fuel corresponds to the maximum PCT.[48]

The increased stored energy (caused by a heavy crud layer) and the delay in the transfer of that stored energy to the coolant during the blowdown phase would increase the PCT and cause the cladding to be subjected to extremely high temperatures for a substantially longer time duration than if the cladding where clean at the onset of the LOCA. This would provide more time for heatup and degradation of the fuel and cladding, including rapid oxidation and embrittlement of the cladding. When the cladding reacts with steam, an exothermic reaction occurs which generates heat, additionally heating up the cladding. Regarding the significance of time and temperature during a LOCA, NRC staff member, Ralph Meyer, states:

> [I]n 10 CFR 50.46, part [b]...[t]here is an oxidation limit of 17[%]. This is really a *time* limit because it was understood at the beginning and we know it now that the embrittling process does not take place on the surface where the oxide is accumulating [during a LOCA]. It is related to the

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[46] NRC, "River Bend Station – NRC Problem Identification and Resolution Inspection Report 0500458/2005008," Report Details, p.10.

[47] "Safety Evaluation by the Office of Nuclear Reactor Regulation, Topical Report BAW-10231P, 'COPERNIC Fuel Rod Design Computer Code,' Framatome Cogema Fuels, Project No. 693," 2002, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML020070158, p. 10.

[48] NRC, "Safety Evaluation by the Office of Nuclear Reactor Regulation, Topical Report WCAP-15063-P, Revision 1, 'Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)'," pp. 7-8.

> diffusion of oxygen in the metal. The diffusion process and the oxidation process run at about the same speed. And so an oxidation limit was used. It [is] very convenient. ... It gives you a nearly constant number that you can use as a limit. ... [A] basic LOCA transient calculation is just *time* and *temperature*. And then you run along with that some equation for oxidation and get a calculated oxidation amount during the transient [emphasis added].[49]

Regarding oxidation-induced cladding embrittlement, "Compendium of ECCS Research for Realistic LOCA Analysis" states:

> Embrittled cladding can fragment upon introduction of the emergency cooling water in a severe accident. During a high-temperature transient accident, the cladding becomes embrittled by steam oxidation of the zircaloy cladding and the formation of thick reaction layers of brittle oxide and oxygen-stabilized alpha zircaloy. The extent of cladding oxidation, and hence embrittlement, is a function of *temperature*, *time*, and the supply of steam and zircaloy. Embrittlement of the cladding may lead to loss of coolable geometry and is thus relevant to the safety analysis of fuel rods [emphasis added].[50]

The increase of the stored energy (caused by a heavy crud layer) and the delay in the transfer of that stored energy to the coolant would also increase the time until quench. As cited before, "Compendium of ECCS Research for Realistic LOCA Analysis" states, "[t]he amount of residual thermal energy [in the fuel rod] influences the *time* required to quench the reactor core with emergency cooling water [emphasis added]."[51]

Furthermore (not mentioned by Klapproth), at the onset of the LOCA, there would already be severe cladding degradation, massive oxidation and absorption of hydrogen at some locations, which would contribute to a loss of cladding ductility. (At TMI-1 Cycle 10 in a failed fuel rod there was absorption of hydrogen to the extent that "hydrided material seems to have broken away from the outer portions of the cladding."[52] And hydrogen content was also measured on a non-failed rod at 700 parts per million

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[49] NRC, Advisory Committee on Reactor Safeguards 539th Meeting Transcript, February 2, 2007, located at: http://www.nrc.gov/reading-rm/doc-collections/acrs/tr/fullcommittee/2007/ac020207.pdf (accessed on 02/27/07), pp. 15-16.

[50] NRC, NUREG-1230, "Compendium of ECCS Research for Realistic LOCA Analysis," p. 6.14-6.

[51] Id., p. 6-14-2.

[52] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 342.

(“ppm”).[53] And oxidation had perforated the cladding in some locations and oxide layers were measured at over 100 μm thick at other locations.) Additionally, during blowdown and also during reflood the amount of coolant flow past cladding with heavy crud and oxide layers would be substantially less than the flow past clean cladding.

(It is significant that the increased stored energy in the fuel because of a heavy crud layer would be substantially greater than that calculated by an ECCS design (a computer code) based on clean cladding. And that the increased severity of the fuel and cladding degradation (*e.g.*, the severity of the cladding oxidation and embrittlement) and its effect on obstructing coolant flow would be substantially greater than those calculated by an ECCS design based on clean cladding.)

3. There is Little or No Evidence that Crud has Ever been Properly Factored into PCT Calculations for Postulated LOCAs.

As already discussed, the increased stored energy in the fuel and its effect on increasing cladding temperatures during a LOCA, and its effect on delaying the transfer of stored energy to the coolant during the blowdown phase, is very significant for how cladding would behave during a LOCA. However, there is little or no evidence that crud has ever been properly factored into PCT calculations for postulated LOCAs for nuclear power plants. An attachment to a letter dated June 17, 2003 from Gary W. Johnsen, RELAP5-3D Program Manager, Idaho National Engineering and Environmental Laboratory (“INEEL”), to Robert H. Leyse states:

> [W]e are not aware of any user who has modeled crud on fuel elements with SCDAP/RELAP5-3D. ... We suspect that none of the other [severe accident analysis] codes have been applied to consider [fuel crud buildup] (because it has not been demonstrated conclusively that this effect should be considered). ... SCDAP/RELAP5-3D *can* be used to consider this effect, it is simply that users have not chosen to consider this phenomen[on] [emphasis not added].[54]

An example of not properly factoring the thermal conductivity of crud into a PCT calculation for a postulated LOCA is in “Callaway Plant, 10 CFR 50.46 Annual Report,

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[53] Id., p. 347.

[54] From an attachment of a letter from Gary W. Johnsen, RELAP5-3D Program Manager, INEEL to Robert H. Leyse, June 17, 2003, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML032050508.

ECCS Evaluation Model Revisions," dating from 2002. It states, "+4.0°F Cycle 6 crud deposition penalty has been deleted. A PCT penalty of 0°F has been assessed for 4 mils [(~100 µm)] of crud, provided BOL conditions remain limiting. In the event that the SBLOCA cumulative PCT becomes ≥ 1700°F, this issue must be reassessed."[55] Clearly, little attention was given to the thermal resistance of the heavy crud layer at Callaway Cycle 6 (1993), which affected high-duty, one-cycle cladding, at the upper spans 4, 5, and 6 of the fuel assembly.[56]

4. The Non-Conservatism of Not Factoring Crud into PCT Calculations.

The fact that a heavy crud layer would increase the quantity of stored energy in the fuel at the onset of a LOCA is significant; it means that the value of the PCT would also increase, above that of fuel with the same burnup, sheathed within clean cladding. (Of course, this does not hold for fresh, BOL fuel, because such fuel has clean cladding at the beginning of its use.) And heavily crudded one-cycle fuel has a higher quantity of stored energy in the fuel than BOL fuel. It has been documented that crud has caused cladding temperatures to increase by over 300 or 600°F during operation. Furthermore, the effects of crud can be quick; *e.g.*, at TMI-1 Cycle 10, one-cycle fuel had a cladding perforation detected, caused by corrosion, only 121 days into the cycle. It is also significant that most of the cladding that experienced crud-induced corrosion failures recently at PWRs was high-power, one-cycle cladding,[57] and that crud layers approximately 100 µm thick at Callaway Cycle 6 were on high-power, one-cycle cladding.[58]

Therefore, a heavy crud layer will increase the quantity of stored energy in the fuel (high-power, one-cycle fuel) to quantities higher than that of fresh, BOL fuel or fuel

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[55] Union Electric Company, "Callaway Plant, 10 CFR 50.46 Annual Report, ECCS Evaluation Model Revisions," October 14, 2002, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML023010263, Attachment 2, p. 6, note 3.

[56] Bo Cheng, David Smith, Ed Armstrong, Ken Turnage, Gordon Bond, "Water Chemistry and Fuel Performance in LWRs."

[57] NRC, Advisory Committee on Reactor Safeguards, Reactor Fuels Subcommittee Meeting Transcript, September 30, 2003, p. 235.

[58] See Bo Cheng, David Smith, Ed Armstrong, Ken Turnage, Gordon Bond, "Water Chemistry and Fuel Performance in LWRs," see also Union Electric Company, "Callaway Plant, 10 CFR 50.46 Annual Report, ECCS Evaluation Model Revisions," 2002, Attachment 2, p. 6, note 3.

with burnups between 30 to 35 GWd/MTU (sheathed within clean cladding), the times of life or burnups considered to have the maximum stored energy that fuel has during operation. The values of the stored energy in BOL fuel or fuel with burnups between 30 to 35 GWd/MTU are what are used to calculate PCTs during postulated LOCAs by computer codes because the maximum stored energy in the fuel corresponds to the maximum PCT.[59]

(Fresh, BOL or one-cycle fuel with low burnups are usually the conditions of the fuel that are considered to have the maximum stored energy, and to yield the highest PCTs for postulated LOCAs. At a NRC, ACRS, Subcommittee Meeting on Materials, Metallurgy, and Reactor Fuels, in January 2007, Mitch Nissley of Westinghouse, cited data from sample LOCA calculations that showed that one-cycle fuel from burnups of zero to approximately 20 or 25 GWd/MTU yielded the highest PCTs. He also stated that at burnups of around 30 GWd/MTU there is an approximate 10% reduction in achievable power, which yields PCTs that are approximately 100°C lower than those of fresher fuel.[60])

It is significant that the stored energy of fuel sheathed within heavily crudded and oxidized cladding is substantially greater than that of fuel of the same burnup, sheathed within clean cladding. And significant that the stored energy of fuel (high-power, one-cycle fuel) sheathed within heavily crudded and oxidized cladding is substantially greater than the BOL quantities of stored energy that are factored into calculating the PCTs of postulated LOCAs. For example, when Westinghouse did LOCA related calculations for the AP1000 (a recently certified nuclear power plant design), scenarios of heavily crudded and oxidized cladding were not included in the PCT calculations done for the safety evaluations of the certification process. (The PCTs were calculated for the

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[59] "Safety Evaluation by the Office of Nuclear Reactor Regulation, Topical Report BAW-10231P, 'COPERNIC Fuel Rod Design Computer Code,' Framatome Cogema Fuels, Project No. 693," p. 10. WCOBRA/TRAC calculates that fresh, BOL fuel has the maximum stored energy in fuel; COPERNIC and FRAPCON-3 calculate that mid-life fuel with burnups of about 30 to 35 GWd/MTU have the maximum stored energy.

[60] NRC, Advisory Committee on Reactor Safeguards, Materials, Metallurgy, and Reactor Fuels Subcommittee Meeting Transcript, January 19, 2007, located at: http://www.nrc.gov/reading-rm/doc-collections/acrs/tr/subcommittee/2007/mm011907.pdf (accessed on 02/27/07), pp. 251-252.

quantity of stored energy in BOL fuel, with the WCOBRA/TRAC code.[61]) Hence, the AP1000 PCTs were not calculated for the maximum stored energy that fuel can attain during operation: recent experiences with fuel at TMI-1, Palo Verde Unit 2, and Seabrook were not considered. This is also true of PCT calculations that have helped qualify recent power uprates at a number of nuclear power plants.

5. Crud and Axial Offset Anomaly.

Axial offset anomaly ("AOA") or CIPS (crud induced power shift) is a phenomenon caused by crud deposition on cladding; it helps provide an indication of how frequently crud affects the operation of nuclear power plants. AOA occurs in PWRs when crud deposits on cladding have a level of boron sufficient to reduce the rate of fission in the vicinity of the crud. "NRC Information Notice 97-85: Effects of Crud Buildup and Boron Deposition on Power Distribution and Shutdown Margin" provides a brief description of AOA and how it occurs:

> High core power results in increased subcooled nucleate boiling in the upper core, which, in turn, causes greater crud accumulation on the fuel assemblies. Lithium borate is absorbed and concentrated in the crud layer, reducing the fission rate in the upper portion of the core. ... As a result of the reduced fissioning in the upper core, the power distribution shifts toward the bottom of the core.[62]

AOA is caused by crud deposits on fuel rods; therefore, the number of occurrences of AOA helps provide an indication of how often fuel rods have crud deposits that are at least 35 μm thick, which is approximately the minimum thickness of crud that enables AOA to occur. However, there can also be crud deposits on fuel rods thicker than 35 μm that do not cause AOA, because not all crud deposits have the quantity of boron that causes AOA. As mentioned before, the thickest layer of crud to be

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[61] *AP1000 Final Safety Evaluation Report*, Chapter 21, "Testing and Computer Code Evaluation," 2004, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML033290640, pp. 21.A-26, 21.A-27, 21-106.

[62] NRC, "NRC Information Notice 97-85: Effects of Crud Buildup and Boron Deposition on Power Distribution and Shutdown Margin," December 11, 1997, located at: http://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/1997/in97085.html (accessed on 01/21/07).

measured in a PWR was 125 μm thick (it caused AOA but not cladding perforations). As of 2003 more than 30 fuel cycles in 16 U.S. PWRs had exhibited AOA.[63]

Current problems caused by crud at PWRs—AOA among them—are discussed in EPRI document "2006 Portfolio, 41.002 Fuel Reliability" as follows:

> Extended fuel cycle operation and power up-rates have increased fuel duty appreciably since the 1980s. Accompanying this transition to higher duty cores have been many crud-related incidents causing anomalous and unanticipated core behavior in pressurized water reactors, fuel integrity problems, and adverse radiological events. These included axial offset anomaly as well as fuel failure cases in which crud played a significant role. ... [AOA] is a phenomenon where anomalous neutron flux behavior has been observed at many plants operating with high-energy cores. Excessive crud deposition creates operational difficulties for plant operators and has safety implications. [AOA] bears an immediate threat to nuclear power's competitiveness; utilities would like to solve this problem as soon as possible.[64]

AOA is detectable during the operation of PWRs; if necessary, after it is detected, a plant can be operated at a lower power level, as H. A. Sepp of Westinghouse points out:

> Several PWRs have experienced [AOAs] due to buildup of boron within crud deposits, in portions of the reactor core which experience subcooled boiling. AOA is characterized by axial power distributions that are more skewed to the bottom of the core than would be expected. These AOA are detectable, and are closely monitored to ensure that adequate shutdown margins can be maintained. In extreme cases, reductions in operating power level have been required to maintain adequate shutdown margin.[65]

What Sepp describes is a case of reducing operating power according to the severity of AOAs, not according to the thickness of crud deposits. In PWRs there can be heavy crud deposits with low levels of boron; in such cases there would only be slight AOAs or no AOAs at all. For example, TMI-1 Cycle 10 had only a slight AOA even though it had enough crud to induce corrosion fuel failures. In common practice, if a

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[63] U. S. Department of Energy, Nuclear Energy Plant Optimization ("NEPO"), "Current NEPO Projects," located at: http://nepo.ne.doe.gov/NEPO2002projects.asp (accessed on 01/21/07).

[64] EPRI, "2006 Portfolio, 41.002 Fuel Reliability," located at: http://www.epriweb.com/public/2006_P041-002.pdf (accessed on 01/21/07), pp. 2-3.

[65] Attachment of a letter from H. A. Sepp, Manager, Regulatory and Licensing Engineering, Westinghouse Electric Company to Annette L. Vietti-Cook, Secretary of the Commission, NRC, December 17, 2001, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML020530290.

heavy crud layer was detected during plant operation that did not cause an AOA, it is unlikely that the operating power level would be reduced, because the thermal resistance of the crud and how it would raise the PCT in the event of a LOCA would most likely not be considered problematic.

6. Crud-Induced Cladding Corrosion Failures at River Bend Cycles 8 and 11.

a. River Bend Cycle 8

At River Bend, a boiling water reactor, during fuel cycle 8, from 1998 to 1999, cladding was perforated by crud-induced oxidation. Discussing these crud-induced fuel failures at River Bend Cycle 8, the paper "Water Chemistry and Fuel Performance in LWRs" states, "[f]uel failures occurred in high duty fuel in its first cycle of operation due to heavy crud deposition... A total of [seven] bundles failed; most failed rods were high peaking rods within these bundles. Some high power bundles had such heavy crud loading that the crud nearly bridged the gap between adjacent rods..."[66] (It is significant that most of the fuel rods that experienced crud-induced corrosion failures recently at PWRs—TMI-1 Cycle 10, Palo Verde Unit 2 Cycle 9, and Seabrook Cycle 5—were also high-power, one-cycle rods.)

"Recent GE BWR Fuel Experience" discusses the crud-induced corrosion failures experienced at River Bend during cycle 8:

> [T]he fuel condition was observed to be highly unusual as characterized by a thick, non-uniform layer of reactor system corrosion products (crud). ... With the high thermal resistance provided by the thick crud layer, augmented with copper, elevated cladding temperatures were developed that then resulted in acceleration of the oxidation process to the point of failure. The failure mechanism exhibits similarities to the earlier [crud-induced localized corrosion ("CILC")] experiences, although the basic CILC mechanism involved a distinct interaction between the copper-based crud and oxide nodules, where copper-based crud intrusion into the oxide nodules produced a local steam blanketing and locally high heat transfer resistance. ... [T]he initial oxide film was uniform (no nodular oxide). The very heavy non-uniform crud layer acted to concentrate the available

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[66] Bo Cheng, David Smith, Ed Armstrong, Ken Turnage, Gordon Bond, "Water Chemistry and Fuel Performance in LWRs."

> copper. The combined heavy crud layer, augmented with copper, produced an effective insulating layer.[67]

Discussing the temperatures to which cladding was subjected at River Bend during cycle 8, "River Bend Station – NRC Problem Identification and Resolution Inspection Report 0500458/2005008" states:

> The crud increased the thermal resistance between the fuel cladding and the coolant such that cladding surface temperatures were substantially higher than would normally be expected. Normal cladding surface temperatures are about 560°F (close to the bulk coolant temperature). General Electric (the fuel vender) calculated that the cladding surface temperatures approached 1200°F in localized areas. The higher temperatures increased the cladding oxidation rate and, at approximately [one] year into the cycle, the cladding oxidation layer extended the entire way through the cladding, creating [perforations].[68]

The crud layer was measured at up to 55 mils thick (~1375 μm).[69] The crud layer was non-uniform; it was composed of an outer layer of fluffy crud, hematite or iron oxide (Fe_2O_3) and magnetite, a different form of iron oxide (Fe_3O_4), and an inner layer of copper oxide (CuO), which precipitated into the pores of a thick tenacious layer of spinel (Fe_3O_4). The inner tenacious layer of crud was apparently less than 100 μm thick.[70] And the oxide thickness "on [the] high power unfailed HGE [(first-burned fuel)] bundles was [measured at] up to [six] mils [(~150 μm)] at the 50 [inch] level, where the cladding perforations occurred."[71] In 1999, River Bend had Zr-2 fuel rod cladding that had a cladding thickness of .813 mm (813 μm).[72] So at River Bend Cycle 8 the equivalent

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[67] Gerald A. Potts, "Recent GE BWR Fuel Experience," American Nuclear Society, Proceedings of the *2000 International Meeting on LWR Fuel Performance*, Park City, Utah, April 10-13, 2000.

[68] NRC, "River Bend Station – NRC Problem Identification and Resolution Inspection Report 0500458/2005008," 02/28/06, Report Details, p.10, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML060600503.

[69] Gerald A. Potts, "Recent GE BWR Fuel Experience."

[70] NRC, "River Bend Station – NRC Problem Identification and Resolution Inspection Report 0500458/2005008," Report Details, p.12, states that the tenacious crud was less than the amount that occurred at River Bend during cycle 11 (~100 μm).

[71] Entergy, River Bend Station – Unit 1, "Licensee Event Report 50-458/99-016-00," March 1, 2000, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML003692155, p. 5.

[72] *World Nuclear Industry Handbook, 1999*, Nuclear Engineering International (England), p. 224.

cladding reacted (ECR) was 100% in the locations were oxidation had perforated the cladding, and for non-failed rods it was approximately 11.8%.[73] The combined effects of the crud and oxide layers were enough to increase cladding temperatures from around 560°F to temperatures approaching 1200°F.

The question, like before, is: how much would the thermal resistance of the crud and oxide cause cladding temperatures to increase during a LOCA? Would the peak cladding temperature (PCT) have exceeded 2200°F (~1204°C) in the event of a LOCA at River Bend Cycle 8? At the inception of a postulated LOCA at the 50 inch elevation of the fuel assembly there would be a 150 μm oxide layer and a 55 mil (~1375 μm) non-uniform crud layer, with an inner tenacious layer, less than 100 μm thick, that had already raised the cladding temperature from 560°F to a temperature approaching 1200°F (293°C to 649°C).

Regarding the issue of what the PCT would have been in the event of a LOCA at River Bend Cycle 8, "Licensee Event Report 50-458/99-016-00" states:

> The peak clad temperature (PCT) for HGE fuel [first-burned fuel] was calculated to have been 1700°F or less. This still demonstrates substantial margin to the 10 CFR 50.46 PCT limit of 2200°F. Note that *excluding* the oxide buildup during steady state operation, the peak local clad oxidation due to LOCA would remain well below the 17% requirement of 10 CFR 50.46, as there would have been no appreciable change in the percent of clad participating in the Metal-Water Reaction under LOCA conditions [emphasis added].[74]

But there are problems with "Licensee Event Report ("LER") 50-458/99-016-00." Although this report was filed in 2000, it ignores guidelines for calculating ECR that are stated in "NRC Information Notice 98-29: Predicted Increase in Fuel Rod Cladding Oxidation," which states that the oxidation considered for ECR during a postulated LOCA "includes both pre-accident oxidation and oxidation occurring during a LOCA."[75] The River Bend LER ignores the fact that the non-failed rods already had an ECR of

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[73] This percentage is calculated by dividing the oxide thickness (150 μm) by 1.56 (the value 1.56 is derived from the atomic weights of the elements involved in the chemical reaction of oxygen and Zircaloy cladding) and then dividing that value (96.2 μm) by the cladding thickness (813 μm).

[74] Entergy, River Bend Station – Unit 1, "Licensee Event Report 50-458/99-016-00," p. 6.

[75] NRC, "NRC Information Notice 98-29: Predicted Increase in Fuel Rod Cladding Oxidation."

approximately 11.8%. It is highly probable that calculating the ECR during a LOCA, by factoring in the 150 μm oxide layer, would have yielded an ECR exceeding 17%, on the non-failed, first-burned fuel rods. As already stated, for the failed, perforated rods, ECR was already 100%.

Additionally, it is highly probable that the PCT would have exceeded 1700°F in the event of a LB LOCA. "The River Bend Station Updated Safety Analysis Report" (RBS USAR) states that the PCT at River Bend for cladding in GE11 fuel bundles (used during cycle 8), for a postulated LOCA, is 1580°F. As already stated, crud and oxide layers on the cladding had increased cladding temperatures from 560°F to temperatures approaching 1200°F (at around the 50 inch elevation). (RBS USAR states that the typical cladding temperature, during plant operation at River Bend, is 578°F.) Typically, during a postulated LOCA the PCT occurs approximately 60% above the base of the active core. Assuming this was the case at River Bend Cycle 8, Petitioner estimates that temperatures would be approximately 1280 to 1380°F on clean cladding at the 50 inch elevation during a postulated LOCA (approximately 300 to 200°F less than the PCT), because the PCT at River Bend was calculated at 1580°F. (Of course, this is a simple assessment: the phenomena occurring during a LOCA are very complex; the actual elevation of the PCT for clean cladding at River Bend, around 1998, can be researched, as well as what the temperature would have been at the 50 inch elevation for clean cladding.) And that the temperature at the 50 inch elevation, during cycle 8 (because crud and oxide layers had already increased the temperature at that elevation by at least 600°F), during a postulated LB LOCA would have with high probability substantially exceeded 1700°F, the value of the PCT reported in "LER 50-458/99-016-00."

In 2000, when "LER 50-458/99-016-00" was filed there was not a great deal of knowledge regarding the values for the thermal conductivity of crud and how crud layers should be modeled in severe accident analysis codes. This is still the case in 2007. In 2008 EPRI plans to complete a technical report titled "Effect of BWR Tenacious Crud on Heat Transfer."[76] (However, it is unlikely that the EPRI report will discuss the impact of crud on the PCTs of light-water reactors ("LWRs") during postulated LOCAs.) And as already discussed, there is little or no evidence that crud has ever been properly factored

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[76] EPRI, "2006 Portfolio, 41.002 Fuel Reliability," p. 4.

into PCT calculations for simulated LOCAs at nuclear power plants. In 2003, Gary W. Johnsen of INEEL stated, "we are not aware of any user who has modeled crud on fuel elements with SCDAP/RELAP5-3D. ... We suspect that none of the other [severe accident analysis] codes have been applied to consider [fuel crud buildup] (because it has not been demonstrated conclusively that this effect should be considered). ... SCDAP/RELAP5-3D *can* be used to consider this effect, it is simply that users have not chosen to consider this phenomen[on] [emphasis not added]."[77]

Therefore, there is reason to believe that with high probability the PCT would have exceeded 2200°F at River Bend Cycle 8 in the event of a LB LOCA. Currently, severe accident analysis codes have no realistic simulation of what would happen to cladding with heavy crud and oxide layers in the event of a LOCA.

The design basis for the emergency core cooling system ("ECCS") at River Bend—for clean cladding, without heavy crud and oxide layers—is described in Chapter 6.3 of the RBS USAR. It states that at the onset of a LOCA, the cladding surface temperature would be in the range of 578°F, and that the PCT would be 1580°F. However, with heavy crud and oxide layers on the cladding (the conditions of cycle 8) the ECCS design basis for River Bend is substantially non-conservative in at least the following aspects: 1) the cladding surface temperature (at some locations) at River Bend Cycle 8 has been reported to have reached temperatures approaching 1200°F; therefore, the starting temperature in the event of a LOCA would be almost 1200°F, not the licensing basis for temperatures around 578°F; 2) the stored energy in the fuel with cladding that had surface temperatures approaching 1200°F (at some locations) would be substantially greater than that of fuel with cladding surface temperatures in the range of 578°F at the onset of a LOCA; 3) the amount of coolant in the vicinity of cladding with heavy crud and oxide layers at the onset of a LOCA would be substantially less than if the cladding were clean; 4) during blowdown and also during reflood the amount of coolant flow past cladding with heavy crud and oxide layers would be substantially less than the flow past clean cladding; 5) the increased quantity of the stored energy in the fuel and the delay in the transfer of that stored energy to the coolant caused by a heavy

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[77] From an attachment of a letter from Gary W. Johnsen, RELAP5-3D Program Manager, INEEL to Robert H. Leyse.

crud layer (mentioned by Klapproth in his letter to the NRC) would cause the cladding to be subjected to extremely high temperatures for a substantially longer time duration than the time duration used in the licensing basis, providing more time for heatup and degradation of the fuel and cladding; 6) the severity of the fuel and cladding degradation occurring in the event of a LOCA and its effect on obstructing coolant flow would be substantially greater than those calculated by an ECCS design based on clean cladding; 7) the increased quantity of the stored energy in the fuel and the delay in the transfer of that stored energy to the coolant would increase the time until quench; 8) at the onset of a LOCA, there would already be severe cladding degradation, massive oxidation and absorption of hydrogen at some locations, which would contribute to a loss of cladding ductility. (These same deficiencies in the design basis for the ECCS at River Bend—for situations where cladding is heavily crudded and oxidized—also apply to the design basis for the ECCS at other nuclear power plants.)

Because the ECCS design basis for River Bend is substantially non-conservative when it comes to calculating the PCT for a postulated LOCA for conditions where there are heavy crud and oxide layers on the cladding, there is reason to believe that with high probability the PCT in the event of a LB LOCA at River Bend Cycle 8 would have exceeded 2200°F (and that the plant would have violated other requirements of 10 C.F.R. § 50.46(b)).

b. River Bend Cycle 11

In a letter to the NRC, dated April 8, 2002, James F. Klapproth of GE Nuclear Energy, discussing what occurred at River Bend Cycle 8, stated, "[t]his unique condition of heavy crud buildup has occurred only once in over 1000 reactor years of BWR operation."[78] However, essentially the same cladding condition occurred again at River Bend Cycle 11 (October 2001 to March 2003), a few years after cycle 8.[79]

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[78] Letter from James F. Klapproth, Manager, Engineering and Technology, GE Nuclear Energy to Annette L. Vietti-Cook, Secretary of the Commission, NRC.

[79] NRC, Advisory Committee on Reactor Safeguards, Reactor Fuels Subcommittee Meeting Transcript, September 30, 2003, pp. 246-247.

Discussing how heavy crud deposits caused fuel failures at River Bend Cycle 11, the paper "Fuel Failures During Cycle 11 at River Bend"[80] states:

> The cause of failure in River Bend rods during Cycle 11 was determined to be accelerated oxidation of the cladding in Span 2 resulting from unusually heavy deposits of insulating tenacious crud. The most probable cause of the insulating tenacious crud was that copper and zinc were available in sufficient quantity to plug either the normal wick boiling paths within the crud or any delamination within the crud or clad oxide, resulting in diminished heat transfer in local areas of the cladding surface.[81]

Additionally, the paper "An Integrated Approach to Maximizing Fuel Reliability"[82] states:

> [A] ~100 μm crud flake [was] retrieved from River Bend [at the] end of cycle 11 where crud-induced fuel failures were experienced. The crud had ~50% porosity with voids and steam chimneys. Localized deposition of Zn, Cu and Si appears to have plugged up some of the steam chimneys, which is believed to have degraded the heat transfer capacity of the tenacious crud.[83]

During cycle 11, a total of six ATRIUM-10 fuel assemblies with burnups in the range of 14.6 to 19.0 GWd/MTU had fuel failures. About 14 months into cycle 11, the first two assemblies that had fuel failures were detected. And at the end of cycle 11, 40 one-cycle assemblies were removed, including the six that had fuel failures. These failures occurred in span two on high power, one-cycle rods (at an elevation of about 20 to 40 inches), where there were heavy crud and oxide layers.[84]

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[80] Edward J. Ruzauskas and David L. Smith, "Fuel Failures During Cycle 11 at River Bend," American Nuclear Society, Proceedings of the *2004 International Meeting on LWR Fuel Performance*, Orlando, Florida, September 19-22, 2004, pp. 221-228.

[81] Id., p. 221.

[82] Rosa Yang, Odelli Ozer, Kurt Edsinger, Bo Cheng, Jeff Deshon, "An Integrated Approach to Maximizing Fuel Reliability," pp. 11-17.

[83] Id., p. 14.

[84] Edward J. Ruzauskas and David L. Smith, "Fuel Failures During Cycle 11 at River Bend," pp. 221-222.

Cladding temperatures have been estimated to have approached 1200°F during cycle 11 (as during cycle 8), because of heavy layers of crud and oxide.[85] (Incidentally, during cycle 11, high temperatures caused significant fuel rod bowing in addition to fuel failures.)[86] RBS USAR states that the PCT for a postulated LOCA at River Bend for cladding in ATRIUM-10 fuel bundles is 1875°F (about 300°F higher than the PCT for GE11 fuel bundles). Typically, during a postulated LOCA the PCT occurs approximately 60% above the base of the active core. Assuming this was the case at River Bend Cycle 11, Petitioner estimates that temperatures would be approximately 1575 to 1675°F at the upper portion of the span-two elevation (around 40 inches) of the fuel assembly during a postulated LOCA for clean cladding (where temperatures would have been approximately 300 to 200°F less than the PCT), because the PCT at River Bend was calculated at 1875°F for ATRIUM-10 fuel bundles. (Of course, this is a simple assessment: the phenomena occurring during a LOCA are very complex; the actual elevation of the PCT for clean cladding at River Bend, around 2001, can be researched, as well as what the temperature would have been at the 40 inch elevation for clean cladding.) And that temperatures at the span-two elevation, during cycle 11 (because layers of crud and oxide had already increased the temperature at that elevation by at least 600°F), in the event of a LB LOCA would have with high probability exceeded 2200°F. (As already discussed, the ECCS design basis for River Bend is substantially non-conservative when it comes to calculating the PCT for a postulated LOCA for conditions where there are heavy crud and oxide layers on cladding.)

c. Why it is Highly Probable that River Bend Cycles 8 and 11 Operated in Violation of 10 C.F.R. § 50.46(b).

In his letter, dated April 8, 2002, to the NRC, discussing River Bend Cycle 8, Klapproth states:

> The primary effects of the heavy crud layer during a postulated LOCA would be an increase in the fuel stored energy at the onset of the event, and a delay in the transfer of that stored energy to the coolant during the

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[85] NRC, "River Bend Station – NRC Problem Identification and Resolution Inspection Report 0500458/2005008," Report Details, p.12, states that the maximum cladding temperatures were similar at River Bend during cycles 8 and 11.

[86] Id., p. 13.

> blowdown phase of the event. However, it is noted that the axial elevation of the heavy crud deposits at [River Bend] was at the lower elevations of the fuel assembly, as is typical of crud deposition behavior in a BWR. The more limiting axial elevations during a postulated LOCA occur at the upper elevations of the fuel assembly, where even in [River Bend], the crud characteristics were normal. Therefore, the heavy crud condition is expected to have no significant effect on the fuel response to a postulated LOCA.[87]

Klapproth accurately describes how the heavy crud layer at River Bend Cycle 8 would have caused the fuel to have greater stored energy than if the cladding were clean and would have caused "a delay in the transfer of...stored energy to the coolant during the blowdown phase of the event." However, he is incorrect in his assertion that the heavy crud layer, because it was located at the lower elevations of the fuel assemblies during cycle 8, would have had no significant effect on the fuel response to a LOCA.

The lower elevation of the heavy crud layer is not a compensating factor for the following deficiencies in the LOCA analyses for heavily crudded cladding at River Bend in at least the following aspects: 1) the cladding surface temperature (at some locations) at River Bend Cycle 8 has been reported to have reached temperatures approaching 1200°F; therefore, the starting temperature in the event of a LOCA would be almost 1200°F, not the licensing basis for temperatures around 578°F; 2) the stored energy in the fuel with cladding that had surface temperatures approaching 1200°F (at some locations) would be substantially greater than that of fuel with cladding surface temperatures in the range of 578°F at the onset of a LOCA; 3) the amount of coolant in the vicinity of cladding with heavy crud and oxide layers at the onset of a LOCA would be substantially less than if the cladding were clean; 4) during blowdown and also during reflood the amount of coolant flow past cladding with a heavy crud layer would be substantially less than the flow past clean cladding; 5) the increased quantity of the stored energy in the fuel and the delay in the transfer of the stored energy to the coolant caused by a heavy crud layer would cause the cladding to be subjected to extremely high temperatures for a substantially longer time duration than the time duration used in the licensing basis, providing more time for heatup and degradation of the fuel and cladding; 6) the increased

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[87] Letter from James F. Klapproth, Manager, Engineering and Technology, GE Nuclear Energy to Annette L. Vietti-Cook, Secretary of the Commission, NRC.

degradation of the fuel and cladding occurring during the extended duration of the extremely high temperatures would further obstruct reflood coolant flow; 7) the increased quantity of the stored energy in the fuel and the delay in the transfer of that stored energy to the coolant would increase the time until quench; 8) at the onset of a LOCA, there would already be severe cladding degradation, massive oxidation and absorption of hydrogen at some locations, which would contribute to a loss of cladding ductility.

Therefore, it is highly probable that River Bend Cycle 8 (and cycle 11) operated in violation of 10 C.F.R. § 50.46(b).

In its entirety, 10 C.F.R. § 50.46(b) states:

> (1) *Peak cladding temperature.* The calculated maximum fuel element cladding temperature shall not exceed 2200°F.
>
> (2) *Maximum cladding oxidation.* The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation. As used in this subparagraph total oxidation means the total thickness of cladding metal that would be locally converted to oxide if all the oxygen absorbed by and reacted with the cladding locally were converted to stoichiometric zirconium dioxide. If cladding rupture is calculated to occur, the inside surfaces of the cladding shall be included in the oxidation, beginning at the calculated time of rupture. Cladding thickness before oxidation means the radial distance from inside to outside the cladding, after any calculated rupture or swelling has occurred but before significant oxidation. Where the calculated conditions of transient pressure and temperature lead to a prediction of cladding swelling, with or without cladding rupture, the unoxidized cladding thickness shall be defined as the cladding cross-sectional area, taken at a horizontal plane at the elevation of the rupture, if it occurs, or at the elevation of the highest cladding temperature if no rupture is calculated to occur, divided by the average circumference at that elevation. For ruptured cladding the circumference does not include the rupture opening.
>
> (3) *Maximum hydrogen generation.* The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.
>
> (4) *Coolable geometry.* Calculated changes in core geometry shall be such that the core remains amenable to cooling.

> (5) *Long-term cooling*. After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.

Furthermore, Klapproth's letter implies that—from General Electric's point of view—there would have been trouble at River Bend Cycle 8 if a LOCA had occurred and the heavy crud and oxide layers had been located at the upper elevations of the fuel assembly. This is significant because at another BWR (in 2002) there was heavy corrosion at the upper elevations of 300 fuel-rod assemblies; a total of 63 of these assemblies had fuel rods that failed (most likely, at the upper elevations). Browns Ferry-2 Cycle 12 (April, 2001 to March, 2003) operated with thick oxide layers at the upper elevations of the fuel rods.[88] It is also significant that the heavy crud and oxide layers that caused overheating and cladding perforations at Three Mile Island-1 Cycle 10 were located at the upper elevations of the fuel assemblies.

7. Current Trends: the Increase of Fuel Failures in Recent Years.

Regarding the recent trend of corrosion-related fuel failures at BWRs, a paper presented in 2004 states:

> [An] increase in BWR failures is due to a great extent to [four] cases that have affected a large number of fuel assemblies. One of these cases is clearly related to crud-accelerated corrosion failures. The other three are also corrosion-related failures and are currently under investigation. The root cause of the failures or the reason for the high crud levels has not been established yet. The analysis is complicated because of coolant chemistry changes introduced for IGSCC and dose control, and the *lack of understanding* of the interplay among materials, fuel duty and the water chemistry variables [emphasis added]."[89]

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[88] TA Keys, James F. Lemons, Conrad Ottenfeld, "Fuel Corrosion Failures in the Browns Ferry Nuclear Plant," American Nuclear Society, Proceedings of the *2004 International Meeting on LWR Fuel Performance*, Orlando, Florida, September 19-22, 2004, pp. 229-231.

[89] Rosa Yang, Odelli Ozer, Kurt Edsinger, Bo Cheng, Jeff Deshon, "An Integrated Approach to Maximizing Fuel Reliability," p. 11.

The same paper also reported that crud or corrosion related fuel failures had occurred at BWRs in six of the years from 1997 to 2004.[90]

For hundreds of LWRs worldwide, after decades of operating experience, heavy crud and/or oxide layers on cladding remain in the realm of operating experience. Moreover, power uprates and longer fuel cycles increase the likelihood of heavy crud and/or oxide layers on cladding. Discussing current trends in the nuclear industry for both BWRs and PWRs an EPRI document, "2006 Portfolio, 41.002 Fuel Reliability," states:

> [T]he overall industry fuel failure rate has risen in the last couple of years as increased fuel duty and new water chemistry environments have presented increasing challenges to cladding integrity in today's extended fuel cycle operation. [Additionally], front-end economics and reliability are not always harmonious. Fuel vendor research and development, for example, has been significantly scaled back to keep the business competitive, while utilities are operating the fuel more aggressively than ever before.[91]

One of the consequences of the current trend of operating fuel more aggressively is that nodular corrosion has reappeared at BWRs. In 2000, it appeared that nodular corrosion had more or less been eliminated from BWR cladding. A paper presented in 2000, "Water Chemistry and Fuel Performance in LWRs," reports:

> Since the mid-1980s, nodular corrosion on Zircaloy fuel cladding, which was implicated in the mechanism of a form of crud-induced fuel failures, namely, CILC [crud-induced localized corrosion], has gradually disappeared in BWRs. Today's Zircaloy-2 cladding is essentially nodular corrosion free.[92]

But in 2004, nodular corrosion was reported to have been observed again in BWRs; a paper presented in 2004, "An Integrated Approach to Maximizing Fuel Reliability," stated:

> Nodular corrosion has recently been observed at several BWRs. Preliminary data indicates that nodular corrosion >50 μm at the upper elevations (> 100-120 inches) of fuel rods and assembly components, such

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[90] Id.

[91] EPRI, "2006 Portfolio, 41.002 Fuel Reliability," p. 1.

[92] Bo Cheng, David Smith, Ed Armstrong, Ken Turnage, Gordon Bond, "Water Chemistry and Fuel Performance in LWRs."

> as water rods and spacers could cause accelerated hydrogen absorption and concentrations in excess of 600 ppm.[93]

The reemergence of nodular corrosion in BWRs is just one of the consequences of the current trend of increasing fuel duty and extending the length of fuel cycles. It also illustrates that the industry is often incorrect when it claims that things like nodular corrosion (in BWRs) are things of the past. It also may be an indication that the problems with crud and oxide that occurred at River Bend Cycles 8 and 11, and at TMI-1 Cycle 10, will continue to plague the nuclear industry in years to come. But if the NRC acts quickly and implements regulations that would help ensure that both BWRs and PWRs do not operate with thicknesses of crud and oxide on cladding that with high probability could cause violations of 10 C.F.R. § 50.46(b), nuclear power plants would operate more safely.

B. Appendix K to Part 50—ECCS Evaluation Models, and the Stored Energy in Fuel Sheathed within Crudded and Oxidized Cladding.

Appendix K to Part 50—ECCS Evaluation Models I(A)(1), *The Initial Stored Energy in the Fuel,* requires that "[t]he steady-state temperature distribution and stored energy in the fuel before [a] hypothetical accident...be calculated for the burn-up that yields the highest calculated cladding temperature (or, optionally the highest calculated stored energy)."

Clearly, the primary purpose of Appendix K to Part 50, regarding the stored energy in the fuel, is to require that the stored energy in the fuel be calculated that "yields the highest calculated cladding temperature" or PCT. So because layers of crud and/or oxide increase the quantity of stored energy in the fuel, Appendix K to Part 50 should require that the thermal conductivity of layers of crud and/or oxide be factored into calculations of the stored energy in the fuel.

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[93] Rosa Yang, Odelli Ozer, Kurt Edsinger, Bo Cheng, Jeff Deshon, "An Integrated Approach to Maximizing Fuel Reliability," p. 15.

To calculate "the steady-state temperature distribution and stored energy in the fuel...for the burn-up that yields the highest calculated cladding temperature" Appendix K to Part 50 requires that:

> [T]he *thermal conductivity* of the UO2...be evaluated as a function of burn-up and temperature, taking into consideration differences in initial density, and the *thermal conductance* of the gap between the UO2 and the cladding...be evaluated as a function of the burnup, taking into consideration fuel densification and expansion, the composition and pressure of the gases within the fuel rod, the initial cold gap dimension with its tolerances and cladding creep [emphasis added].

The "thermal conductivity of the UO2" and the "thermal conductance of the gap between the UO2 and the cladding" are obviously important for calculating "the steady-state temperature distribution and stored energy in the fuel...for the burn-up that yields the highest calculated cladding temperature," so it seems obvious that the effect of the thermal conductivity of layers of crud and/or oxide that increases the stored energy in the fuel should also be taken into account for this calculation. There is evidence that crud and oxide layers on cladding have, in some instances, caused cladding temperatures during operation to increase over 600°F.[94] And if the cladding temperature increases over 600°F, it means that the stored energy in the fuel has also increased substantially.

As previously cited, Klapproth, regarding how a heavy crud layer would increase the initial stored energy in the fuel during a LOCA, states, "[one of the] primary effects of [a] heavy crud layer during a postulated LOCA would be an increase in the fuel stored energy at the onset of the event."[95]

The fact that a heavy crud layer would increase the quantity of stored energy in the fuel at the onset of a LOCA is significant; it means that the value of the PCT would also increase, above that of fuel with the same burnup, sheathed within clean cladding. (Of course, this does not hold for fresh, BOL fuel, because such fuel has clean cladding at the beginning of its use.) And heavily crudded one-cycle fuel has a higher quantity of stored energy in the fuel than BOL fuel. It has been documented that crud has caused

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[94] NRC, "River Bend Station – NRC Problem Identification and Resolution Inspection Report 0500458/2005008," Report Details, p.10.

[95] Letter from James F. Klapproth, Manager, Engineering and Technology, GE Nuclear Energy to Annette L. Vietti-Cook, Secretary of the Commission, NRC.

cladding temperatures to increase by over 300 or 600°F during operation. Furthermore, the effects of crud can be quick; *e.g.*, at TMI-1 Cycle 10, one-cycle fuel had a cladding perforation detected, caused by corrosion, only 121 days into the cycle. It is also significant that most of the cladding that experienced crud-induced corrosion failures recently at PWRs was high-power, one-cycle cladding,[96] and that the cladding that experienced crud-induced corrosion failures at River Bend Cycles 8 and 11 was high-power, one-cycle cladding,[97] and that crud layers approximately 100 μm thick at Callaway Cycle 6 were on high-power, one-cycle cladding.[98]

Regarding instructions for calculating the quantity of stored energy in the fuel—for heavily crudded cladding—Appendix K to Part 50 is non-conservative. A heavy crud layer will increase the quantity of stored energy in the fuel (high-power, one-cycle fuel) to quantities higher than that of fresh, BOL fuel or fuel with burnups between 30 to 35 GWd/MTU (sheathed within clean cladding), the times of life or burnups considered to have the maximum stored energy that fuel has during operation. The values of the stored energy in BOL fuel or fuel with burnups between 30 to 35 GWd/MTU are what are used to calculate PCTs during postulated LOCAs by computer codes because the maximum stored energy in the fuel corresponds to the maximum PCT.[99]

(Fresh, BOL or one-cycle fuel with low burnups are usually the conditions of the fuel that are considered to have the maximum stored energy, and to yield the highest PCTs for postulated LOCAs. At a NRC, ACRS, Subcommittee Meeting on Materials, Metallurgy, and Reactor Fuels, in January 2007, Mitch Nissley of Westinghouse, cited data from sample LOCA calculations that showed that one-cycle fuel from burnups of zero to approximately 20 or 25 GWd/MTU yielded the highest PCTs. He also stated that at burnups of around 30 GWd/MTU there is an approximate 10% reduction in achievable

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[96] NRC, Advisory Committee on Reactor Safeguards, Reactor Fuels Subcommittee Meeting Transcript, September 30, 2003, p. 235.

[97] See Bo Cheng, David Smith, Ed Armstrong, Ken Turnage, Gordon Bond, "Water Chemistry and Fuel Performance in LWRs;" see also Edward J. Ruzauskas and David L. Smith, "Fuel Failures During Cycle 11 at River Bend," pp. 221-222.

[98] Bo Cheng, David Smith, Ed Armstrong, Ken Turnage, Gordon Bond, "Water Chemistry and Fuel Performance in LWRs."

[99] "Safety Evaluation by the Office of Nuclear Reactor Regulation, Topical Report BAW-10231P, 'COPERNIC Fuel Rod Design Computer Code,' Framatome Cogema Fuels, Project No. 693," 2002, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML020070158, p. 10.

power, which yields PCTs that are approximately 100°C lower than those of fresher fuel.[100])

It is significant (and hazardous) that an ECCS design based on the requirements of Appendix K to Part 50 (or any NRC approved best-estimate ECCS evaluation models used in lieu of Appendix K) is non-conservative when it comes to calculating the quantity of stored energy in one-cycle fuel with heavy crudded cladding.

C. The Effect of Cladding Hydrogen Content on Cladding Embrittlement.

An increase in cladding hydrogen content contributes to cladding embrittlement. The following citation from the transcript of proceedings of NRC, ACRS, Reactor Fuels Subcommittee, April 4, 2001, relates the opinions of two experts regarding hydrogen-content's role in reducing cladding ductility:

> Hee Chung [of Argonne National Laboratory] now points out that for Zircaloy, that there seems to be a threshold around 600 or 700 ppm hydrogen. When you get that much hydrogen in the specimen, then it also contributes to the reduction of ductility. .... Griger [of KFKI Atomic Energy Research Institute] believes that he sees a threshold [for a reduction of ductility for Zircaloy] at a much lower level, down around 150 to 200 [ppm].[101]

At TMI-1 Cycle 10, there was massive absorption of hydrogen in cladding. In rod 011 (a failed rod, discussed earlier), there was absorption of hydrogen to the extent that "hydrided material seems to have broken away from the outer portions of the cladding."[102] And cladding hydrogen content was measured on a non-failed rod at 700 ppm.[103] Therefore, it is highly probable that rod 011 absorbed at least 700 ppm of hydrogen at locations of its upper elevation. (As discussed earlier, rod 011 also had a 111.1 μm oxide layer.) Incidentally, this value for hydrogen content in one-cycle

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[100] NRC, Advisory Committee on Reactor Safeguards, Materials, Metallurgy, and Reactor Fuels Subcommittee Meeting Transcript, January 19, 2007, located at: http://www.nrc.gov/reading-rm/doc-collections/acrs/tr/subcommittee/2007/mm011907.pdf (accessed on 02/27/07), pp. 251-252.

[101] NRC, Advisory Committee on Reactor Safeguards, Reactor Fuels Subcommittee Meeting Transcript, April 4, 2001, located at: http://www.nrc.gov/reading-rm/doc-collections/acrs/tr/subcommittee/2001/rf010404.html (accessed on 01/21/07).

[102] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 342.

[103] Id., p. 347.

cladding is similar to values that have been measured in high-burnup cladding: at (PWR) H. B. Robinson-2, high-burnup cladding hydrogen content was measured at 800 ppm.[104]

Some of the cladding at TMI-1 Cycle 10 had levels of hydrogen content which, according to the findings of Chung, of Argonne National Laboratory, would have caused a loss of cladding ductility. This would be in addition to the embrittlement caused by the excessive oxidation of the cladding.

IV. PROPOSED ACTIONS

The NRC needs to require all holders of operating licenses for nuclear power plants to operate such plants at operating conditions (*e.g.*, levels of power production, fuel-cycle lengths, and light-water coolant chemistries) necessary to effectively limit thicknesses of crud and/or oxide layers on cladding. New regulations are needed for reactor-operation parameters, uranium-oxide and mixed-oxide fuel, and cladding, in order to ensure that cladding is free of unsafe thicknesses of crud and/or oxide, which in turn would help ensure that nuclear power plants operate in compliance with 10 C.F.R. § 50.46(b).

The NRC also needs to require all holders of operating licenses for nuclear power plants to factor the thermal-resistance effects of crud and/or oxide layers on cladding into their calculations of PCTs for postulated LOCAs at their plants. The NRC also needs to consider these effects when reviewing 10 C.F.R. § 50.46 reports and before approving power uprates and new nuclear power plants, like the recently certified AP1000. The thermal-resistance effects of crud and/or oxide layers on cladding increase the stored energy in the fuel. Therefore, Petitioner requests that the 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 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. Appendix K should also provide instructions for how to carry out calculations that factor in the role that the thermal resistance of crud and/or oxide layers on cladding

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[104] NRC, Advisory Committee on Reactor Safeguards, Reactor Fuels Subcommittee Meeting Transcript, July 27, 2005, located at: http://www.nrc.gov/reading-rm/doc-collections/acrs/tr/subcommittee/2005/rf072705.pdf (accessed on 01/21/07), p. 99.

plays in determining the quantity of stored energy in the fuel at the onset of a postulated LOCA. These requirements also need to apply to any NRC approved best-estimate ECCS evaluation models used in lieu of Appendix K calculations.

Presently, Appendix K does not refer to the effects that crud and/or oxide layers on cladding have on increasing the stored energy in the fuel or provide instructions for calculating the quantity of stored energy in the fuel by factoring in the thermal resistance of crud and/or oxide layers; yet Appendix K does state that the "stored energy in the fuel before [a] hypothetical accident shall be calculated" to determine the PCT. Appendix K needs to be updated because there is extensive evidence that the thermal resistance of crud and/or oxide layers on cladding plays a role in determining the stored energy in the fuel. By including the thermal resistance of crud and/or oxide, calculations would more accurately determine the quantity of stored energy in the fuel (and the PCT) during a postulated LOCA. Additionally, these phenomena are not considered (nor are their effects calculated) by any NRC approved best-estimate ECCS evaluation models used in lieu of Appendix K calculations.

Additionally, the NRC needs to amend 10 C.F.R. § 50.46 to include a regulation stipulating a maximum allowable percentage of hydrogen content in cladding. 10 C.F.R. § 50.46 needs to be updated because there is extensive evidence that hydriding of cladding—like oxidation of cladding—contributes to cladding embrittlement. These requirements also need to apply to any NRC approved best-estimate ECCS evaluation models used in lieu of Appendix K calculations.

V. RATIONALE FOR THE NEEDED CHANGES

Crud and/or oxide layers on cladding surfaces cause the temperature of fuel rods to increase during the operation of nuclear power plants (sometimes in excess of 300°F or even 600°F). The low thermal conductivity of crud and/or oxide inhibits heat transfer, causing the cladding temperature to increase; temperatures also increase in the fuel sheathed within the cladding (*i.e.*, the stored energy in the fuel increases). In the event of a LOCA, the thermal resistance of insulating layers of crud and/or oxide on cladding, and increased fuel temperatures, will cause the PCT to be higher than it would be if the cladding were clean. If a LB LOCA had occurred in recent years at several nuclear power plants that operated with heavy crud and/or oxide layers, there is a high probability that the PCT would have exceeded 2200°F. New regulations that ensure that plants prevent unsafe thicknesses of crud and/or oxide layers on cladding from occurring during operation would substantially reduce risks to public and plant-worker safety and help ensure that plants operate in compliance with 10 C.F.R. § 50.46(b).

If Appendix K is amended to require that calculations of the quantity of stored energy in the fuel for postulated LOCAs factor in the effects of the thermal resistance of crud and/or oxide layers on cladding, the results of such calculations would be more accurate. And if Appendix K provides instructions for how such calculations should be carried out to factor in the thermal resistance of crud and/or oxide layers on cladding, those instructions would help utilities monitor and operate plants in compliance with 10 C.F.R. § 50.46(b). This would also be true if these phenomena are considered (and their effects are calculated) by NRC approved best-estimate ECCS evaluation models used in lieu of Appendix K calculations.

Hydriding of cladding—like oxidation of cladding—contributes to cladding embrittlement. If 10 C.F.R. § 50.46 (and all NRC approved best-estimate ECCS evaluation models used in lieu of Appendix K calculations) is updated to include a regulation stipulating a maximum allowable percentage of hydrogen in cladding, it would better help plants prevent cladding embrittlement during plant operation and in the event of LOCAs.

VI. CONCLUSION

At the NRC's 539th ACRS Meeting, in February 2007, Jennifer Uhle, Deputy Division Director of Materials Engineering in the Office of Nuclear Regulatory Research, stated that the current criteria of 10 C.F.R. § 50.46 are non-conservative.[105] When discussing possible revisions to 10 C.F.R. § 50.46 at the same meeting, and at the NRC's ACRS, Materials, Metallurgy, and Reactor Fuels Subcommittee Meeting, in January 2007, there was concern that high-burnup fuel with cladding degradation, high levels of oxidation and hydriding, would exceed the 17% oxidation limit in the event of LOCAs at

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[105] NRC, Advisory Committee on Reactor Safeguards 539th Meeting Transcript, February 2, 2007, located at: http://www.nrc.gov/reading-rm/doc-collections/acrs/tr/fullcommittee/2007/ac020207.pdf (accessed on 02/27/07), pp. 8, 10.

nuclear power plants. The guideline of "NRC Information Notice 98-29," stipulating that the "[t]otal oxidation [of cladding] includes both pre-accident oxidation and oxidation occurring during a LOCA"[106] is being considered for regulation status for a new revised version of 10 C.F.R. § 50.46, due in 2009.[107]

At the January 2007 meeting, NRC staff member Ralph Meyer stated that the purpose of the 17% limit (and the 2200°F limit) was to ensure that cladding ductility was retained, by remaining below those limits, in the event of a LOCA.[108] He also provided examples regarding cladding ductility where the value 1.2 (the F factor[109]) was multiplied by the pre-accident ECR in order to calculate the remaining percentage of oxidation allowed to occur during a LOCA.[110] He explained that the F factor "depends most strongly on the temperature transient, on heat-up rates and cool-down rates," and that there could be "several different...transients that [would] have different heat-up rates and cool-down rates, and [that 1.2] is sort of a middle of the road value."[111] (A NRC regulatory guide states that the F factor can vary from 1 to 1.6.)[112]

At the January 2007 meeting Meyer cited the following "worst case zircaloy," postulated-LOCA example:

> [W]e have a de facto corrosion limit [that is] used in safety analyses of 100 microns, and zircaloy can get that much corrosion on it if you push it hard enough. And so [I have] taken this example right at the limit. So this would be what I call a worst case zircaloy example, and the 100 microns is about [10%] ECR, and you multiply that by 1.2, subtract the 12 from 17, and you get five percent, a fairly small number."[113]

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[106] NRC, "NRC Information Notice 98-29: Predicted Increase in Fuel Rod Cladding Oxidation."
[107] See NRC, Advisory Committee on Reactor Safeguards, Materials, Metallurgy, and Reactor Fuels Subcommittee Meeting Transcript, January 19, 2007, p. 245; see also NRC, Advisory Committee on Reactor Safeguards 539th Meeting Transcript, February 2, 2007, p. 10.
[108] NRC, Advisory Committee on Reactor Safeguards, Materials, Metallurgy, and Reactor Fuels Subcommittee Meeting Transcript, January 19, 2007, p. 13.
[109] Id., pp. 179-182.
[110] Id., pp. 31-33.
[111] Id., p. 31.
[112] Id., pp. 181-182.
[113] Id., p. 33.

At the January 2007 meeting, in response to Meyer's "worst-case zircaloy" example, Mitch Nissley of Westinghouse Electric Company, stated:

> [W]e anticipated an F factor on the order of 1.5 or 1.6, and I went through and did a shorthand calculation just to show this was similar to Dr. Meyer's use of the 100 micron Zr-4 design limit. One hundred microns...is effectively a design limit at least for Westinghouse fuel, for all of our cladding types. ... If you use a large F factor, [you have] got no room to work with with curb design limits on fuel.[114]

Then to argue that high-burnup fuel would not be subjected to extremely high temperatures in the event of a LOCA, Nissley added:

> Once [the fuel] starts to burn down in terms of its achievable power levels, achievable peak cladding temperatures and the corresponding transient oxides drop off dramatically, and that comment is valid for all break sizes, both large and small beaks. The important conclusion from this [is that] high burnup fuel [used in the U.S.] cannot [have PCTs that] approach 1200[°C].[115]

Then, after citing data from sample LOCA calculations that demonstrated that one-cycle fuel from burnups of zero to approximately 20 or 25 GWd/MTU yielded the highest PCTs,[116] Nissley concluded:

> I showed you in that one example [LB LOCA] calculation that even using more or less an upper bound for the high burnup fuel in terms of relative power, it was more than 1000[°F], less limiting than the fresh fuel. I think the real message here is [we have] done a lot of testing at 1200[°C] with high burnup fuel. The double-sided [oxidation] reaction is also a limit that I know of to [occur at] very high temperature[s, above approximately 1100°C[117]]. [A]nd [with high burnup fuel] you just [cannot reach temperatures that high].[118]

The conclusion to be drawn from Nissley's argument is that the F factor would only apply to cladding encasing high-burnup fuel that would not have enough power (or stored energy) to reach PCTs above temperatures where rapid oxidation occurs. Hence, pre-accident oxidation (and the phenomena the F factor accounts for) would not cause a

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[114] Id., p. 243.
[115] Id., pp. 250-251.
[116] Id., p. 251.
[117] Id.
[118] Id., p. 261.

loss of cladding ductility for properly managed high-burnup fuel in the event of a LOCA.[119]

However, Nissley did not mention scenarios involving one-cycle fuel of burnups between zero and 25 GWd/MTU, with heavily crudded cladding. Such fuel would yield higher PCTs than the examples he cited. Furthermore, the cladding, in such scenarios, where there are crud-induced corrosion failures, would be more degraded than that of Meyer's "worst-case zircaloy" example, where cladding had an ECR value of 10%. At TMI-1 Cycle 10, cladding was measured with approximately 10% ECR and at River Bend Cycle 8, ECR was measured at approximately 12%; however, there were also cladding perforations due to corrosion at those plants, so their maximum ECR was actually 100% on one-cycle, high-powered fuel. The fuel at TMI-1 Cycle 10 and River Bend Cycle 8 (and any other nuclear power plant with crud-induced corrosion failures on one-cycle, high power fuel rods) would yield higher PCTs than BOL fuel; and this fuel was encased within cladding that was more degraded than that of Meyer's "worst case zircaloy" example. Hence, such fuel is similar to BOL fuel but it yields even higher PCTs, and such cladding is similar to high-burnup cladding but it is even more degraded.

Uhle is certainly correct that the current criteria of 10 C.F.R. § 50.46 are non-conservative, though the NRC still has not addressed the extent of this non-conservatism. For example, the NRC has not addressed the role that the thermal resistance of crud and oxide layers on cladding play in determining the quantity of stored energy in the fuel at the onset of a postulated LOCA. Meanwhile, the NRC currently allows utilities to operate "fuel more aggressively than ever before."[120]

It is pertinent that the EPRI document titled "2006 Portfolio, 41.002 Fuel Reliability" refers to the "many operational surprises utilities have experienced recently"[121] at nuclear power plants. This document states that among the operational surprises were "higher than expected [levels of] cladding corrosion and hydriding."[122] Petitioner would add higher than expected levels of crud.

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[119] This is discussed in more detail in NRC, Advisory Committee on Reactor Safeguards 539th Meeting Transcript, February 2, 2007, pp. 60-64.

[120] EPRI, "2006 Portfolio, 41.002 Fuel Reliability," p. 1.

[121] Id., p. 2.

[122] Id.

In recent years at nuclear power plants there have been levels of corrosion of cladding that in the event of a LOCA would with high probability cause violations of 10 C.F.R. § 50.46(b)(2), and thicknesses of crud and oxide on cladding that in the event of a LB LOCA would with high probability cause additional violations of 10 C.F.R. § 50.46(b). This is unsatisfactory from a safety standpoint and should not become a new norm for how the nuclear industry operates its plants.

If the NRC forces utilities to stop operating the fuel in nuclear power plants as aggressively as it currently allows, perhaps the many operational surprises of recent years would cease or be substantially reduced. And if the NRC considers the effects that the thermal resistance of crud and/or oxide layers on cladding have on increasing PCTs when reviewing 10 C.F.R. § 50.46 reports, reviewing plants for power upgrades, and reviewing new plant designs, perhaps many additional operational surprises would be prevented. If implemented, the regulations and amendments proposed in this petition would improve public and plant-worker safety.

Respectfully submitted,

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Dated: March 15, 2007

From: <mel2005@columbia.edu>
To: <secy@nrc.gov>
Date: Sat, Mar 17, 2007 3:10 AM
Subject: Petition; Attn: Rulemakings and Adjudications Staff

Dear Ms. Vietti-Cook:

Attached to this email in a PDF file is a petition for rulemaking, submitted pursuant to 10 C.F.R. 2.802. An additional copy of this petition will promptly be mailed to the U.S. Nuclear Regulatory Commission.

Sincerely,

Mark Edward Leyse

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