7/31/08
73FR 44778

RULES AND DIRECTIVES BRANCH USNRC

September 5, 2008 (7)

2008 SEP -8 AM 11:43

Michael Lesar
Chief, Rulemaking, Directives and Editing Branch
Office of Administration
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

RECEIVED

Attention: Rulemaking and Adjudications Staff

Subject: Response to the Nuclear Regulatory Commission's (NRC's) notice of solicitation of public comments on documents under consideration to establish the technical basis for new performance-based emergency core cooling system requirements

Dear Mr. Lesar:

Enclosed is my response to the NRC's notice of solicitation of public comments on documents under consideration to establish the technical basis for new performance-based emergency core cooling system ("ECCS") requirements, published in the Federal Register, July 31, 2008.

My name is Mark Edward Leyse; I submitted a petition for rulemaking (ADAMS Accession No. ML070871368, Docket PRM-50-84) to the NRC, dated March 15, 2007, requesting new regulations, regarding limiting the thickness of crud (corrosion products) and/or oxide layers on fuel cladding surfaces, and stipulating a maximum allowable percentage of hydrogen content in fuel cladding; I also requested that the NRC amend Appendix K to Part 50—ECCS Evaluation Models. PRM-50-84 was summarized briefly in the American Nuclear Society's *Nuclear News*'s June 2007 issue[1] and commented on and deemed "a well-documented justification for...recommended changes to the [NRC's] regulations"[2] by the Union of Concerned Scientists. I am a private citizen concerned about nuclear safety issues; my father, Robert H. Leyse, worked for several decades in the nuclear industry, and worked on two of the PWR Full Length Emergency Cooling Heat Transfer tests mentioned in Appendix K to Part 50.

[1] American Nuclear Society, *Nuclear News*, June 2007, p. 64.
[2] Union of Concerned Scientists, Comments on Petition for Rulemaking Submitted by Mark Edward Leyse (Docket No. PRM-50-84), July 31, 2007, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML072130342, p. 3.

SUNSI Review Complete
Template=ADM-013

E-RIDS=ADM-03
Add=P.M.Clifford (PMC3)

In this response to the NRC's notice of solicitation, I will respond to the query, regarding the affects of crud deposits and how crud deposits should be addressed from a regulatory point of view, mentioned in the third section of the notice, "Implementation," on page 44779. The notice states:

> Crud deposits on the fuel cladding surface may affect fuel stored energy, fuel rod heat transfer, and cladding corrosion.
>
> a. What role does plant chemistry and crud deposits play on these items?
>
> b. How should normal and abnormal levels of crud deposits be addressed from a regulatory point of view?

In this response, I cannot "include references to the section and page numbers of the document to which the comments applies," as the notice requested, because the documents under review—"Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46" and "Cladding Embrittlement During Postulated Loss-of-Coolant Accidents"—do not mention any of the affects of crud deposits.

Respectfully submitted,

Mark Edward Leyse
P.O. Box 1314
New York, NY 10025
mel2005@columbia.edu

September 5, 2008

Michael Lesar
Chief, Rulemaking, Directives and Editing Branch
Office of Administration
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

MARK EDWARD LEYSE'S RESPONSE TO THE NUCLEAR REGULATORY COMMISSION'S NOTICE OF SOLICITATION OF PUBLIC COMMENTS ON DOCUMENTS UNDER CONSIDERATION TO ESTABLISH THE TECHNICAL BASIS FOR NEW PERFORMANCE-BASED EMERGENCY CORE COOLING SYSTEM REQUIREMENTS

<u>TABLE OF CONTENTS</u>

I. THE NECESSITY OF MODELING THE AFFECTS OF CRUD AND/OR OXIDE LAYERS ON FUEL AND FUEL CLADDING IN LEGALLY BINDING ECCS EVALUATION CALCULATIONS

The thermal resistance of crud and/or oxide layers on cladding causes cladding and uranium oxide fuel temperatures to increase (sometimes in excess of 270°F[1] or even 600°F[2]) during the operation of nuclear power plants. In the event of a LOCA, the thermal resistance of insulating layers of crud and/or oxide on one-cycle fuel cladding will cause the PCT to be higher than it would be if the cladding were clean.

The NRC must amend Appendix K to Part 50 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 must 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 must apply to any NRC approved best-estimate ECCS evaluation models used in lieu of Appendix K calculations.[3]

Realistically modeling crud and/or oxide layers on fuel cladding in ECCS evaluation calculations, would help ensure that such calculations would comply with 10 C.F.R. § 50.46(a)(1)(i), which requires that "ECCS cooling performance...be calculated...to provide assurance that the most severe postulated loss-of-coolant accidents are calculated." This, in turn, would help ensure that plants operate in compliance with the parameters set forth in 10 C.F.R. § 50.46(b).

---

[1] 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.

[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.

[3] 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.

A. 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. Therefore, because layers of crud and/or oxide increase the quantity of stored energy in the fuel, Appendix K to Part 50 must require that the thermal conductivity of layers of crud and/or oxide be factored into calculations of the stored energy in the fuel.

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;" therefore, 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 must also be taken into account for this calculation.

Regarding how a heavy crud layer would increase the initial stored energy in the fuel during a LOCA, James F. Klapproth, Manager, Engineering and Technology at GE Nuclear Energy, 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."[4]

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 270[5] or 600°F[6] 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.[7] It is also significant that most of the cladding that experienced crud-induced corrosion failures recently at PWRs was high-power, one-cycle cladding,[8] and that the cladding that experienced crud-induced corrosion failures at River Bend Cycles 8 and 11 was high-power, one-cycle cladding,[9] and that crud layers approximately 100 μm thick at Callaway Cycle 6 were on high-power, one-cycle cladding.[10]

---

[4] 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.

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

[6] NRC, "River Bend Station – NRC Problem Identification and Resolution Inspection Report 0500458/2005008," 02/28/06, Report Details, p.10.

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

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

[9] 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.

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

B. Appendix K to Part 50 Already Requires Modeling the Affects of Crud and/or Oxide Layers on Fuel and Fuel Cladding

Although it is not explicitly stated in Appendix K to Part 50, Appendix K to Part 50 already requires modeling the affects of crud and/or oxide layers on fuel and fuel cladding, because the thermal resistance of such layers on cladding increases the fuel rod internal pressure and affects the fuel-cladding gap width. Internal pressure and the status of the fuel-cladding gap width are phenomena that Appendix K to Part 50 currently requires to be factored into calculations of the stored energy in the fuel.

It is essential 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 fuel cladding plays in increasing the stored energy in the fuel. In addition to increasing the stored energy in the fuel, the thermal resistance of crud and/or oxide layers on cladding also increases fuel rod internal pressure.

Regarding this phenomenon, NRC document, "Safety Evaluation by the Office of Nuclear Regulation, Topical Report WCAP-15604-NP. REV. 1, 'Limited Scope High Burnup Lead Test Assemblies' Westinghouse Owners Group, Project No. 694," states:

> Clad[ding] oxidation can lead to significantly increased fuel rod internal pressures. Above certain oxidation levels, the impacts on rod internal pressure and the significant impacts on the cladding pressure limit characteristics could result in the rod internal pressure criterion being exceeded. Therefore, if oxidation is kept to a minimum, the fuel rod internal pressure criterion is less limiting than simply the oxidation criterion by itself. ... In addition to oxidation causing increases in rod internal pressures, crud deposition has a similar effect since crud is a poor conductor of heat. Keeping crud deposition to a minimum also reduces the impact on rod internal pressures.[11]

The "fuel rod internal pressure criterion" referred to in the above citation is "a criterion requiring that the internal pressure of the fuel rod not exceed reactor coolant

---

[11] NRC, "Safety Evaluation by the Office of Nuclear Regulation, Topical Report WCAP-15604-NP. REV. 1, 'Limited Scope High Burnup Lead Test Assemblies' Westinghouse Owners Group, Project No. 694," 2003, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML070740225 (See Section A), p. 4.

system pressure."[12] Concerning cladding sheathing high burnup fuel, "NRC Information Notice 98-29: Predicted Increase in Fuel Rod Cladding Oxidation" explains that fuel-cladding gap reopening may occur "when internal pressure in the [fuel] rod exceeds reactor coolant system pressure."[13] Concerning the possibility of gap reopening due to the low thermal conductivity of oxide layers on high burnup cladding, "NRC Information Notice 98-29" states:

> Using the corrected corrosion model, Westinghouse interpreted the PAD [computer code (Westinghouse Improved Performance Analysis and Design Model)] results to indicate that the degraded thermal conductivity of the cladding due to the higher oxidation levels produced an increase in fuel cladding temperatures and consequent higher clad creep rates. These higher creep rates could, in turn, lead to gap reopening, which would be contrary to a Westinghouse design criterion.[14]

It is significant that the thermal resistance of crud and/or oxide layers on cladding increases the fuel rod internal pressure and affects the fuel-cladding gap width, because internal pressure and the status of the fuel-cladding gap width are phenomena that Appendix K to Part 50 currently requires to be factored into calculations of the stored energy in the fuel. 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].

Clearly, not realistically modeling crud and/or oxide layers in ECCS evaluation calculations would already be a violation of Appendix K to Part 50, because Appendix K to Part 50 requires that ECCS evaluation calculations "[take] into consideration...the

---

[12] 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).
[13] Id.
[14] Id.

composition and pressure of the gases within the fuel rod, the initial cold gap dimension with its tolerances and cladding creep," to determine "the thermal conductance of the gap between the UO2 and the cladding." If ECCS evaluation calculations do not factor in the thermal resistance of crud and/or oxide layers on cladding, such calculations will not properly determine "the thermal conductance of the gap between the UO2 and the cladding" or "the steady-state temperature distribution and stored energy in the fuel." And improperly calculating "the steady-state temperature distribution and stored energy in the fuel" would undermine the primary purpose of Appendix K to Part 50, regarding the stored energy in the fuel: to calculate the stored energy in the fuel that "yields the highest calculated cladding temperature."

It is also significant that, in some cases, thick crud and oxide layers have quickly accumulated on one-cycle cladding sheathing high-duty fuel. (At Three Mile Island Unit 1 Cycle 10, such cladding was perforated by oxidation only 121 days into the cycle.[15]) It is highly probable—because of substantial increases in fuel rod internal pressure—that quickly accumulated layers of crud and oxide on one-cycle cladding sheathing high-duty fuel would slow down fuel-cladding gap closure from normal closure rates, during operation or prevent fuel-cladding gap closure, altogether. And prevent cladding from "creep[ing] down towards the fuel pellets, due to the system pressure exceeding the [fuel] rod internal pressure...relatively early in the first cycle of operation"[16] (as a recent Entergy document, describes clean-cladding behavior at pressurized water reactors). This effect would prevent the reduction of the average temperature "at the hot spot [of the fuel rod] by several hundred degrees [Fahrenheit] relatively early in the first cycle of operation"[17] (as the same Entergy document, describes fuel (sheathed in clean-cladding) behavior).

It is clear that crud and/or oxide layers on cladding affect the stored energy in the fuel in two ways: 1) their external thermal resistance increases the stored energy in the

---

[15] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 339.
[16] Entergy, Attachment 1 to NL-04-100, "Reply to NRC Request for Additional Information Regarding Proposed License Amendment Request for Indian Point 2 Stretch Power Uprate," August 12, 2004, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML042380253, p. 6.
[17] Id.

fuel and 2) their external thermal resistance increases the fuel rod internal pressure and affects the fuel-cladding gap width, which, in turn, affects the thermal conductance of the fuel-cladding gap and the quantity of the stored energy in the fuel. Therefore, it is imperative that the NRC amend Appendix K to Part 50 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, and that Appendix K to Part 50 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. Such requirements also must apply to any NRC approved best-estimate ECCS evaluation models used in lieu of Appendix K calculations.

C. Some of the Guidelines in NUREG-0800, SRP, Section 4.2(II)(3)(C)(i) Fuel Temperatures (Stored Energy), Must be Made into a Legally Binding Regulation

Regarding the effects of corrosion on fuel cladding and some of the guidelines in NUREG-0800, SRP, Section 4.2, Nuclear Energy Institute ("NEI") states:

> It is well recognized that the effects of corrosion on the cladding and grid spacer surfaces and other fuel system structural components need to be considered to ensure that fuel system dimensions remain within operational tolerances and that functional capabilities are not reduced below those assumed in the safety analyses. Guidelines in NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants" (SRP), Section 4.2, "Fuel System Design" do not specify an explicit limit on the maximum allowable corrosion thickness. The guidance contained in SRP Section 4.2 does require that the impact of corrosion on the thermal and mechanical performance be considered in the fuel design analysis, when comparing to the design stress and strain limits. For the fuel rod cladding, the effects include:
>
> (I) The heat transfer resistance provided by the cladding oxide and crud layers, thereby increasing cladding and fuel pellet temperatures,
>
> (II) The metal loss as a result of the corrosion reaction, thereby reducing the cladding load carrying ability.

> These effects are already considered in the design analyses to ensure that the cladding does not exceed the mechanical design limits e.g. design stress and design strain.[18]

The guidelines in NUREG-0800 are not legally binding rules or regulations; *i.e.*, they are "guidelines" for the NRC staff, not legally binding requirements for licensees. (NUREG-0800, SRP, Section 4.2, states: "The SRP is not a substitute for the NRC's regulations, and compliance with it is not required.") The aspects of NUREG-0800, SRP, Section 4.2, cited by NEI, should be made into legally binding regulations for licensees; this would help them operate nuclear power plants more safely.

NUREG-0800, SRP, Section 4.2(II)(3)(C)(i) Fuel Temperatures (Stored Energy) states:

> Fuel temperatures and stored energy during normal operation serve as input to ECCS performance calculations. Temperature calculations require complex computer codes that model many different phenomena. RG [(Regulatory Guide)] 1.157 describes models, correlations, data, and methods to realistically calculate ECCS performance during a LOCA and to estimate the uncertainty in that calculation. Alternatively, an ECCS evaluation model may be developed in conformance with the acceptable features of Appendix K to 10 CFR Part 50. Phenomenological models that should be reviewed include the following:

SRP § 4.2(II)(3)(C)(i) lists 21 of the "phenomenological models that should be reviewed;" the 4th being: "Thermal conductivity of the fuel, cladding, cladding crud, and oxidation layers," the 19th being: "Cladding oxide and crud layer thickness[es]."

These guidelines (and perhaps some of the other guidelines) of SRP § 4.2(II)(3)(C)(i); *i.e.*, modeling the thermal conductivity of the cladding, and crud and/or oxide layers on cladding in ECCS evaluation calculations, must be made into a legally binding regulation, for all holders of operating licenses for nuclear power plants.

If the nuclear industry already conducts such ECCS evaluation calculations by accurately modeling the thermal conductivity of crud and/or oxide layers on cladding, as readily as NEI claims, then NEI and the nuclear industry should not be opposed to

---

[18] Nuclear Energy Institute, Comments on Petition for Rulemaking Submitted by Mark Edward Leyse (Docket No. PRM-50-84), August 3, 2007, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML072150609, p. 2.

making the above mentioned guidelines of SRP § 4.2(II)(3)(C)(i) into a legally binding regulation.

Regarding NRC approved fuel performance models that are used to determine fuel rod conditions at the start of a postulated LOCA, and the fact that they model the impact of crud and oxidation on fuel temperatures and pressures, NEI states:

> Approved fuel performance models are used to determine fuel rod conditions at the start of a postulated LOCA. The impact of crud and oxidation on fuel temperatures and pressures may be determined explicitly or implicitly in the system of models used. The impact of crud and oxidation is addressed, since the system of approved models is benchmarked to temperature and fission gas release data which inherently include corrosion up to high burnup levels.[19]

Again, if the nuclear industry already conducts ECCS evaluation calculations that model "[t]he impact of crud and oxidation on fuel temperatures and pressures…explicitly or implicitly" as readily as NEI claims, then NEI and the nuclear industry should not be opposed to making the above mentioned guidelines of SRP § 4.2(II)(3)(C)(i) into a legally binding regulation.

II. THE NECESSITY OF REGULATIONS LIMITING THE THICKNESS OF CRUD AND/OR OXIDE LAYERS ON FUEL CLADDING SURFACES

The NRC must 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 and/or oxide layers on fuel cladding surfaces. New regulations are needed for reactor-operation procedures, 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 thermal resistance of crud and/or oxide layers on cladding causes cladding and uranium oxide fuel temperatures to increase (sometimes in excess of 270°F or even 600°F in the case of cladding) during the operation of nuclear power plants. In the event

---

[19] Id.

of a LOCA, the thermal resistance of insulating layers of crud and/or oxide on one-cycle fuel cladding will cause the PCT to be higher than it would be if the cladding were clean.

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)).[20] 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 modeled in the calculation).

If a LB LOCA had occurred in recent years at one of the several nuclear power plants that operated with heavy crud and/or oxide layers on one-cycle fuel cladding, 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).

III. BACKGROUND

A. An Example of Crud-Induced Cladding Corrosion Failures at a PWR: Three Mile Island Unit 1 Cycle 10

In 1995, Three Mile Island Unit 1 ("TMI-1"), a 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."[21] Under typical operating conditions at TMI-1 the maximum cladding temperature is 346°C,[22] meaning that crud deposits raised local cladding temperatures by over 100 or 150°C (180 or 270°F) or greater. Therefore, it is highly probable that if a 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.

---

[20] 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.
[21] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 342.
[22] *World Nuclear Industry Handbook, 1995*, Nuclear Engineering International (England), p. 80.

Discussing crud and its effect on increasing cladding temperature, the paper "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10" 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.[23]

At TMI-1 Cycle 10, the first leaking rod (a symptom of a cladding perforation "due to crud induced localized corrosion"[24]) was detected 121 days into the cycle.[25] 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."[26]

After cycle 10, a total of 253 fuel rods in 38 fuel assemblies were observed with a Distinctive Crud Pattern ("DCP")—"a mottled appearance of a dark, nearly black surface with jagged patches of white showing through."[27] Out of the 253 rods observed with a DCP, nine had failed and, based on eddy current measurements, 101 of the rods had thinned, without failure.[28] "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle

[23] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 343.
[24] Id., p. 339.
[25] Id.
[26] Id., p. 342.
[27] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 340.
[28] Id.

10" states that "[s]everal samples from both the sound and failed rods showed recrystallization in the DCP areas of the cladding[; and that t]he recrystallization occurred in an arc of cladding that ranged from 50° to 75° of the outside face of the fuel rod and extended through the entire cladding wall."[29]

In 1995, TMI-1 had PWR Zr-4 fuel-rod cladding with a thickness of .67 mm or 670 μm (microns).[30] After cycle 10, the maximum oxide thickness measured on a fuel rod was 111.1 μm, at an axial elevation of 118.5 inches.[31] 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[32] (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 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."[33] (This is a NRC recommendation for guidance; it is not a legally binding regulation.) (It is also significant, 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.)[34]

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

---

[29] Id., p. 342.
[30] *World Nuclear Industry Handbook 1995*, p. 80.
[31] Id., p. 344.
[32] NRC, Advisory Committee on Reactor Safeguards, Materials, Metallurgy, and Reactor Fuels Subcommittee Meeting Transcript, January 19, 2007, p. 243.
[33] 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.
[34] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 339.

from a pre-accident value of 10.6% to a during-accident value exceeding 17%. My point, however, is not to make an issue out of this supposition about the ECR; after all, during cycle 10, fuel rods had failed due to local corrosion perforations,[35] 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.[36] 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.[37] 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.[38] 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.[39]

1. The Thermal Conductivities of Crud and Zirconium Dioxide

As already mentioned, crud layers increased local cladding surface temperatures by over 180 or 270°F or greater during cycle 10 because the thermal conductivity of the crud was very low. Pertaining to the thermal conductivity of crud, Bo Cheng of Electric Power Research Institute ("EPRI"), at the NRC's Advisory Committee on Reactor Safeguards ("ACRS"), Reactor Fuels Subcommittee, September 30, 2003, stated:

> [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

[35] Id., p. 343.
[36] Id., p. 340.
[37] 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.
[38] Id., pp. 241-242.
[39] Id., p. 133.

> 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 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.[40]

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."[41] This same value for the thermal conductivity of crud is given in NUREG-1230, dating back to 1988.[42] It is evident that—although 0.8648 W/mK is a very low thermal conductivity—Cheng 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.)[43] And he also stated that "crud is...difficult to characterize" and that its thermal "conductivities...depend on [its] morpholog[ies]."[44] (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.)[45] Therefore, it is clear that certain morphologies of crud have thermal conductivities that are less than 0.8648 W/mK and of unknown values.

---

[40] Id., p. 240.
[41] 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.
[42] 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.
[43] 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.
[44] NRC, Advisory Committee on Reactor Safeguards, Reactor Fuels Subcommittee Meeting Transcript, September 30, 2003, p. 240.
[45] 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.

In fact, EPRI currently (to be completed in 2008) has a goal to "[p]erform crud simulation tests to determine the effect of tenacious crud on fuel surface heat transfer."[46] This study is for BWR crud but its results could also be applied to PWRs. As the article "Fuel Crud 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."[47] 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 (ZrO2) or zirconia also has a low thermal conductivity, and is used industrially as an insulating material.[48] 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.[49] Additionally, volume one of the code manual, "Frapcon-3" (published in 1997) states that the current MATPRO function for ZrO2, uses values of approximately 2.0 W/mK for the thermal conductivity of ZrO2 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 ZrO2 at the same temperatures may be much lower, at values close to 1.0 W/mK.[50] 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,

---

[46] 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.
[47] 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).
[48] 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).
[49] K. E. Gilchrist, "Thermal Property Measurements on Zircaloy-2 and Associated Oxide Layers," *Journal of Nuclear Materials*, 62, 1976, pp. 257-264.
[50] 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.[51]

2. 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 the parameter set forth in 10 C.F.R. § 50.46(b)(1).

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.[52] At TMI-1 Cycle 10, the crud layer was observed to be heaviest in span six of the fuel assemblies, which was "the hottest span" of the assemblies during cycle 10.[53] Additionally, the transcript of proceedings from NRC ACRS, Reactor Fuels Subcommittee, September 30, 2003, states

[51] 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.
[52] *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.
[53] See R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 340; see also NRC, Advisory Committee on Reactor Safeguards, Reactor Fuels Subcommittee Meeting Transcript, September 30, 2003, p. 236.

that nine fuel rods failed at the span-six elevation.[54] Crud was also observed in spans five and seven[55] or at elevations from around 80 to 120 inches above the bottom of the end plug[56] (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. (At TMI-1 Cycle 10, the PCT would have most likely occurred in span six: "the hottest span.") 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, during cycle 10, it is 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 at the span-six elevation where rod 011 failed.

It is significant that in rod 011 there was massive absorption of hydrogen, to the extent that "hydrided material seems to have broken away from the outer portions of the cladding."[57] Cladding hydrogen content was measured on a non-failed rod at 700 ppm.[58] Therefore, it is highly probable that rod 011 absorbed at least 700 ppm of hydrogen at locations of its upper elevation. Incidentally, this value for hydrogen content in one-cycle 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.[59]

An increase in cladding hydrogen content contributes to cladding embrittlement. The transcript of proceedings of NRC, ACRS, Reactor Fuels Subcommittee Meeting,

---

[54] NRC, Advisory Committee on Reactor Safeguards, Reactor Fuels Subcommittee Meeting Transcript, September 30, 2003, p. 236.
[55] R. Tropasso, J. Willse, B. Cheng, "Crud-Induced Cladding Corrosion Failures in TMI-1 Cycle 10," p. 340.
[56] Id., p. 344.
[57] Id., p. 342.
[58] Id., p. 347.
[59] 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.

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].[60]

It is also significant that rod 011 was perforated by oxidation and that it had a 111.1 μm oxide layer at the 118.5 inch elevation, because there is "a decrease in Zr-4 cladding ductilities when oxide thicknesses begin to exceed 100 μm."[61]

Because rod 011 was degraded from substantial oxidation and massive absorption of hydrogen it would have been somewhat embrittled during cycle 10. Therefore, if a real-life LB LOCA had occurred during cycle 10, rod 011 would have with high probability been subjected to temperatures exceeding 2200°F and also with high probability fractured and fragmented during the reflood period (of the LOCA) and lost structural integrity.

B. 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

---

[60] 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).
[61] David B. Mitchell and Bert M. Dunn, "Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel," p. xviii.

> pellet, fuel pellet cracking, heat transfer through the fuel cladding gap, *and conduction through the cladding* [emphasis added].[62]

It is significant that the quantity of stored energy in the fuel is partly related to heat transfer through cladding, because crud and oxide layers impede heat transfer through cladding. For this reason, the stored energy in the fuel increases when the cladding sheathing it is heavily crudded and 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."[63]

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 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].[64]

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.

---

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

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

[64] 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.

> 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.[65]

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.[66]

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.

The increase of the stored energy in the fuel caused by a heavy crud layer is substantial (in some cases, enough to increase local cladding temperatures in excess of 270°F or even 600°F during operation).[67] This increase raises the stored energy in the fuel to levels higher than that of fresh, 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

---

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

[66] 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.

[67] NRC, "River Bend Station – NRC Problem Identification and Resolution Inspection Report 0500458/2005008," Report Details, pp.10-12. River Bend, a BWR, operated with local cladding temperatures approaching 1200°F during cycles 8 and 11.

fuel with burnups of about 30 to 35 GWd/MTU have the maximum stored energy.)[68] The quantities 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.[69]

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 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].[70]

---

[68] "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.

[69] 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.

[70] 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.

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].[71]

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]."[72]

C. 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 be affected 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

---

[71] NRC, NUREG-1230, "Compendium of ECCS Research for Realistic LOCA Analysis," p. 6.14-6.
[72] Id., p. 6-14-2.

effect, it is simply that users have not chosen to consider this phenomen[on] [emphasis not added].[73]

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, 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."[74] 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.[75]

A recent paper, "The Chemistry of Fuel Crud Deposits and its Effect on AOA in PWR Plants," describing computer codes that model chemical conditions and heat transfer within crud deposits, helps clarify the magnitude of the error of the Callaway Cycle 6 ECCS evaluation: it states that a crud layer that is 59 μm thick is modeled so that "the rise in temperature [from the water side to the fuel side of the layer] is dramatic, reaching temperatures near 400°C [at the fuel side]," up from around 345°C at the water side of the layer.[76] This means, according to the calculations of these codes, that a 59 μm crud layer increases cladding surface temperatures by approximately 55°C or 100°F during operation. And also, according to the calculations of these codes, that a 100 μm crud layer would increase cladding temperatures by more than 100°F during operation. Therefore, according to these codes, at onset of a postulated LOCA, at Callaway Cycle 6, the temperature of the cladding, at some locations, would be over 100°F higher than it

[73] 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.

[74] 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.

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

[76] Jim Henshaw, John C. McGuire, Howard E. Sims, Ann Tuson, Shirley Dickinson, Jeff Deshon "The Chemistry of Fuel Crud Deposits and Its Effect on AOA in PWR Plants," 2005/2006, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML063390145, p. 8.

would be if the cladding were clean: this would result in a substantially higher than "+4.0°F...crud deposition penalty"[77] for the Cycle 6 calculated PCT.

It is significant that "The Chemistry of Fuel Crud Deposits and its Effect on AOA in PWR Plants" states that the "rise in temperature [across crud layers] was not accounted for in previous models [of crud layers]."[78] And significant that these computer codes that model chemical conditions and heat transfer within crud deposits do not seem to model morphologies of crud that have been documented to increase local cladding temperatures by over 180 or 270°F or greater during PWR operation. Therefore, it is possible that the actual thermal resistance of the crud at Callaway Cycle 6 was greater than what these computer codes would predict. In reality, the increase in temperature across the 100 μm crud layer might have been significantly greater than what these codes would have calculated in 2005/2006, when the paper was written.

D. 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; crud has caused local cladding temperatures to increase by over 270°F during the operation of PWRs. Furthermore, the effects of crud can be quick; *e.g.*, at TMI-1 Cycle 10, one-cycle fuel had a cladding perforation, caused by corrosion, detected 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-

[77] Union Electric Company, "Callaway Plant, 10 CFR 50.46 Annual Report, ECCS Evaluation Model Revisions," Attachment 2, p. 6, note 3.
[78] Jim Henshaw, John C. McGuire, Howard E. Sims, Ann Tuson, Shirley Dickinson, Jeff Deshon "The Chemistry of Fuel Crud Deposits and Its Effect on AOA in PWR Plants," p. 8.

power, one-cycle cladding,[79] and that crud layers approximately 100 μm thick at Callaway Cycle 6 were on high-power, one-cycle cladding.[80]

BOL fuel or fuel with burnups between 30 to 35 GWd/MTU (sheathed within clean cladding) are the times of life or burnups considered to have the maximum stored energy that fuel has during operation. For this reason, the quantities of 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.[81]

(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 the January 2007, NRC, ACRS, Subcommittee Meeting on Materials, Metallurgy, and Reactor Fuels, 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 yield 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 (180°F) lower than those of fresher fuel.)[82]

It is 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 PCTs during postulated LOCAs. PCT calculations that helped qualify power uprates at a number of PWRs were not calculated with the maximum stored energy that fuel can attain during operation:

---

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

[80] 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.

[81] "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.

[82] 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.

recent experiences with fuel at TMI-1, Palo Verde Unit 2, Seabrook, and Callaway were not modeled. Hence, the values of the PCTs generated by these ECCS evaluation calculations are non-conservative. Furthermore, the power uprates that these non-conservative PCTs helped qualify make it highly probable that nuclear power plants will operate in violation of 10 C.F.R. § 50.46(b)(1).

E. An Example of Non-Conservative ECCS Evaluation Calculations that Helped Qualify a Recent Power Uprate at Indian Point Unit 2

ECCS evaluation calculations that qualified the recent Indian Point Unit 2 ("IP-2") stretch power uprate of 3.26%[83] (authorized by the NRC in 2004), were conducted in violation of 10 C.F.R. § 50.46(a)(1)(i). 10 C.F.R. § 50.46(a)(1)(i) states that "ECCS cooling performance must be calculated...to provide assurance that the most severe postulated loss-of-coolant accidents are calculated." The ECCS evaluation calculations that helped qualify the recent IP-2 stretch power uprate did not model scenarios where one-cycle fuel would have heavily crudded and oxidized cladding or would have crud-induced corrosion failures, operating conditions that have occurred at U.S. PWRs in recent years. In the event of a LOCA, such fuel would yield significantly higher peak cladding temperatures ("PCTs") than the fresh, beginning-of-life ("BOL") fuel modeled by the licensee of IP-2.[84] Furthermore, the cladding, in scenarios where crud-induced corrosion failures would occur, would be substantially more oxidized than the maximum oxidation values claimed by the licensee in the ECCS evaluation calculations. Additionally, it is significant that the recent ECCS evaluation calculations for IP-2 did not model "[t]he [dissolved and suspended] solids [in the reactor coolant system water following a LOCA that] might...cling tenaciously to the fuel cladding and compromise the heat transfer meant to occur during the post-LOCA period[, possibly] sufficiently

---

[83] NRC, letter to Entergy, "Indian Point Nuclear Generating Unit No. 2 – Issuance of Amendment Re: 3.26 Percent Power Uprate," October 27, 2004, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML042960007, p. 1.

[84] The PCTs were calculated with Westinghouse's WCOBRA/TRAC computer code. Westinghouse maintains that BOL fuel is the most limiting condition of fuel during LOCAs. See Westinghouse, "Code Qualification Document for Best Estimate Small Break LOCA Analysis; Volume 3: PWR Uncertainties and Sensitivities for Small Break LOCA," 2003, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML031570508, Section 29, p. 25.

imped[ing] the desired heat transfer [enough] to lead to fuel cladding failure due to thermal stresses."[85] NRC, NUREG-1861, "Peer Review of GSI-191 Chemical Effects Research Program," explains that "[t]he coolant water, bearing the dissolved and suspended solids, would flash away as it encountered the hot fuel cladding and reactor vessel surfaces and leave its solids load behind;" and that "the deposited solids could undergo higher temperature hydrothermal reactions and likely undergo self-cementation."[86] For these reasons, it is highly probable that IP-2 is currently operating at unsafe power levels, 3216 megawatts thermal ("MWt"), and highly probable that if a large break (LB) LOCA were to occur at IP-2 under circumstances where one-cycle fuel would have heavily crudded and oxidized cladding or crud-induced corrosion failures, the parameters set forth in 10 C.F.R. § 50.46(b) would be violated.

When Entergy, the licensee of IP-2, did ECCS evaluation calculations to qualify the stretch power uprate for IP-2, the calculated maximum cladding oxidation percentages were calculated for fresh, BOL fuel, with Westinghouse's WCOBRA/TRAC code.[87] Discussing ECCS evaluation calculations of the maximum local oxidation that could occur during a LB LOCA at IP-2 (to qualify the 2004 stretch power uprate), Entergy, states:

> The maximum local oxidation was calculated for fresh fuel, at the beginning of the cycle. This represents the maximum amount of transient oxidation that could occur at any time in life. As burnup increases, the transient oxidation decreases for the following reasons:
>
> 1) The cladding creeps down towards the fuel pellets, due to the system pressure exceeding the rod internal pressure. This will reduce the average internal stored energy at the hot spot by several hundred degrees [Fahrenheit] relatively early in the first cycle of operation. Accounting only for this change, which occurs early in the first cycle, reduces the transient oxidation significantly.
>
> 2) Later in life, the clad creep-down benefit still remains in effect. In addition, with increasing irradiation, the power production from the fuel

[85] NRC, NUREG-1861, "Peer Review of GSI-191 Chemical Effects Research Program," 2006, p. C-24.
[86] Id.
[87] Entergy, Attachment 1 to NL-04-100, "Reply to NRC Request for Additional Information Regarding Proposed License Amendment Request for Indian Point 2 Stretch Power Uprate," August 12, 2004, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML042380253, pp. 6-7.

> will naturally decrease as a result of depletion of the fissionable isotopes. Reductions in achievable peaking factors in the burned fuel relative to the fresh fuel are realized before the middle of the second cycle of operation. The achievable linear heat rates decrease steadily from this point until the fuel is discharged, at which point the transient oxidation will be negligible.[88]

As Entergy states, 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 during postulated LOCAs to yield the maximum amount of transient oxidation (and the highest PCTs) that could occur at any time in the fuel's life. At the January 2007, NRC, Advisory Committee on Reactor Safeguards ("ACRS"), Subcommittee Meeting on Materials, Metallurgy, and Reactor Fuels, 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 yield the highest PCTs (and have the maximum stored energy).[89]

However, Entergy's claim that "the average internal stored energy [will decrease] at the hot spot by several hundred degrees [Fahrenheit] relatively early in the first cycle of operation"[90] is misleading: burnups of 25 GWd/MTU occur in fuel well past the early part of its first cycle of operation. Furthermore, for conditions where cladding would be crudded and oxidized it is highly probable that the cladding would not "[creep] down towards the fuel pellets, due to the system pressure exceeding the [fuel] rod internal pressure...relatively early in the first cycle of operation,"[91] because crud and oxide layers on cladding increase fuel rod internal pressure.

---

[88] Id., p. 6. Fuel-cladding gap closure typically takes place within 500 days of operation for M5 cladding; see "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. 7.

[89] See NRC, Advisory Committee on Reactor Safeguards, Materials, Metallurgy, and Reactor Fuels Subcommittee Meeting Transcript, January 19, 2007, pp. 251-252.

[90] Entergy, Attachment 1 to NL-04-100, "Reply to NRC Request for Additional Information Regarding Proposed License Amendment Request for Indian Point 2 Stretch Power Uprate," August 12, 2004, p. 6.

[91] Id.

Regarding this phenomenon, NRC document, "Safety Evaluation by the Office of Nuclear Regulation, Topical Report WCAP-15604-NP. REV. 1, 'Limited Scope High Burnup Lead Test Assemblies' Westinghouse Owners Group, Project No. 694," states:

> Clad[ding] oxidation can lead to significantly increased fuel rod internal pressures. Above certain oxidation levels, the impacts on rod internal pressure and the significant impacts on the cladding pressure limit characteristics could result in the rod internal pressure criterion being exceeded. Therefore, if oxidation is kept to a minimum, the fuel rod internal pressure criterion is less limiting than simply the oxidation criterion by itself. In addition to oxidation causing increases in rod internal pressures, crud deposition has a similar effect since crud is a poor conductor of heat. Keeping crud deposition to a minimum also reduces the impact on rod internal pressures.[92]

It is significant that, in some cases, thick crud and oxide layers have quickly accumulated on one-cycle cladding sheathing high-duty fuel. At Three Mile Island Unit 1 Cycle 10, such cladding was perforated by oxidation only 121 days into the cycle.[93] Therefore, it is highly probable that quickly accumulated layers of crud and oxide would either slow down or stop the cladding from creeping down towards the fuel pellets, not reducing the average stored energy in the fuel or the average temperature "at the hot spot by several hundred degrees [Fahrenheit] relatively early in the first cycle of operation."[94]

And even more significantly, Entergy does not consider that the stored energy in one-cycle fuel sheathed within heavily crudded and oxidized cladding would increase to levels greater than that of BOL fuel sheathed within clean cladding.

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,

---

[92] NRC, "Safety Evaluation by the Office of Nuclear Regulation, Topical Report WCAP-15604-NP. REV. 1, 'Limited Scope High Burnup Lead Test Assemblies' Westinghouse Owners Group, Project No. 694," 2003, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML070740225 (See Section A), p. 4.

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

[94] Entergy, Attachment 1 to NL-04-100, "Reply to NRC Request for Additional Information Regarding Proposed License Amendment Request for Indian Point 2 Stretch Power Uprate," p. 6.

> and a delay in the transfer of that stored energy to the coolant during the blowdown phase of the event.[95]

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.

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 hydriding, and embrittlement of the cladding.

Regarding the time until quench, Entergy's "Reply to Request for Additional Information Regarding Indian Point 2 Stretch Power Uprate," states:

> In order to demonstrate stable and sustained quench, the WCOBRA/TRAC calculation for the maximum local oxidation analysis was extended. Figure 1 shows the peak cladding temperatures for the five rods modeled in WCOBRA/TRAC. This figure indicates that quench occurs at approximately 275 seconds for the low power rod (rod 5), 400 seconds for the core average rods (rods 3 and 4), and 500 seconds for the hot rod (rod 1) and hot assembly average rod (rod 2). Once quench is predicted to occur, the rod temperatures remain slightly above the fluid saturation temperature for the remainder of the simulation. ... This is consistent with the expected result based on *the removal of the initial core stored energy* [emphasis added]...[96]

The time period until quench for each of the five rods modeled in Entergy's ECCS evaluation calculations would have been significantly increased if scenarios where cladding would be heavily crudded and oxidized had been modeled, because the removal of the initial core stored energy would have taken more time. Because such scenarios were not modeled, Entergy's results for the time period until quench are non-

[95] 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.
[96] Entergy, Attachment 1 to NL-04-121, "Reply to NRC Request for Additional Information Regarding Proposed License Amendment Request for Indian Point 2 Stretch Power Uprate," September 24, 2004, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML042720432, Attachment 1, p. 8.

conservative. And because heavy crud and oxide layers on cladding would cause the cladding to be subjected to extremely high temperatures for a substantially longer time duration than the rods modeled in the ECCS evaluation calculations, there would be substantially more degradation of the fuel and cladding, including rapid oxidation and embrittlement of the cladding. Therefore, the results of Entergy's ECCS evaluation calculations for the maximum cladding oxidation that could occur during a LB LOCA at IP-2 (13.2%)[97] are substantially non-conservative.

Discussing calculations of the maximum local oxidation that could occur during a LB LOCA and the maximum sum of the pre-accident and transient oxidation that could occur at IP-2, Entergy, states:

> [T]he transient oxidation decreases from a very conservative maximum of 13.2% at BOL to a negligible value at EOL [(end of life)], while the pre-transient oxidation increases from zero at BOL to a very conservative maximum at EOL of <15%. Additional WCOBRA/TRAC and HOTSPOT [(with oxidation calculations using "corresponding WCOBRA/TRAC transient boundary conditions")[98]] calculations were performed at intermediate burnups, accounting for burnup effects on fuel performance data (primarily initial stored energy and rod internal pressure). These calculations support the conclusion that the sum of the transient and pre-transient oxidation remains below 15% at all times in life. This conclusion is applicable to each of the fuel designs that will be included in the SPU [(stretch power uprate)] cores, and confirms IP-2 conformance with the 10 CFR 50.46 acceptance criterion for local oxidation.[99]

Entergy's statement that its "calculations support the conclusion that the sum of the transient and pre-transient oxidation remains below 15% at all times in life," is non-conservative. Entergy's analysis omits cladding conditions experienced at PWRs in recent years in the United States where there were crud-induced corrosion fuel failures. In such cases the pre-transient oxidation would have been 100%, because local oxidation perforated cladding at the affected plants.

[97] NRC, letter to Entergy, "Indian Point Nuclear Generating Unit No. 2 – Issuance of Amendment Re: 3.26 Percent Power Uprate," October 27, 2004, located at: www.nrc.gov, Electronic Reading Room, ADAMS Documents, Accession Number: ML042960007, Enclosure 2, p. 18.
[98] Entergy, Attachment 1 to NL-04-100, "Reply to NRC Request for Additional Information Regarding Proposed License Amendment Request for Indian Point 2 Stretch Power Uprate," p. 6.
[99] Id., p. 7.

For conditions where one-cycle fuel would have heavily crudded and/or oxidized cladding or would have crud-induced corrosion failures the current ECCS design basis for IP-2 is substantially non-conservative in at least the following aspects: 1) heavily crudded and oxidized cladding surface temperatures (at some locations) would be higher at the onset of a LOCA than the licensing basis for temperatures based on clean cladding; 2) the stored energy in the fuel sheathed within cladding with heavy crud and oxide layers would be substantially greater than that of fuel sheathed within clean cladding 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 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 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.

Clearly, the 2004 stretch power uprate of 3.26 % for IP-2 was partly qualified by the results of ECCS evaluation calculations that were conducted in violation of 10 C.F.R. § 50.46(a)(1)(i), which requires that "ECCS cooling performance must be calculated…to provide assurance that the most severe postulated loss-of-coolant accidents are calculated." For this reason, it is highly probable that IP-2 is currently operating at an unsafe power level (3216 MWt), in noncompliance with the parameters set forth in 10 C.F.R. § 50.46(b).

F. 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 PWRs. 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.[100]

AOA is caused by crud deposits on fuel rods; therefore, the number of occurrences of AOA helps provide an indication of how often PWR 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.[101] 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 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.[102]

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

[100] 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).

[101] Jim Henshaw, John C. McGuire, Howard E. Sims, Ann Tuson, Shirley Dickinson, Jeff Deshon "The Chemistry of Fuel Crud Deposits and Its Effect on AOA in PWR Plants," p. 7.

[102] 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).

> 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.[103]

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.[104]

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 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.

---

[103] 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.

[104] 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.

G. Examples of Crud-Induced Cladding Corrosion Failures at a BWR: River Bend Cycles 8 and 11

1. 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..."[105] (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 copper. The combined heavy crud layer, augmented with copper, produced an effective insulating layer.[106]

---

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

[106] 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.

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].[107]

The crud layer was measured at up to 55 mils thick (~1375 μm).[108] 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.[109] 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."[110]

In 1999, River Bend had Zr-2 fuel rod cladding that had a cladding thickness of .813 mm (813 μm).[111] Therefore, at River Bend Cycle 8, the equivalent cladding reacted (ECR) was approximately 11.8%,[112] at some locations on non-failed rods and 100% at

---

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

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

[109] 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).

[110] 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.

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

[112] 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

the locations were oxidation had perforated the cladding. 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].[113]

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."[114] The River Bend LER ignores the fact that the non-failed rods already had an ECR of 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

---

and Zircaloy cladding) and then dividing that value (96.2 μm) by the cladding thickness (813 μm).

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

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

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, I estimate 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."[115] (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 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

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

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]."[116]

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 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

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

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)).

2. 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."[117] However, essentially the same cladding condition occurred again at River Bend Cycle 11 (October 2001 to March 2003), a few years after cycle 8.[118]

[117] Letter from James F. Klapproth, Manager, Engineering and Technology, GE Nuclear Energy to Annette L. Vietti-Cook, Secretary of the Commission, NRC.
[118] 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"[119] 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.[120]

Additionally, the paper "An Integrated Approach to Maximizing Fuel Reliability"[121] 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.[122]

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.[123]

---

[119] 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.
[120] Id., p. 221.
[121] Rosa Yang, Odelli Ozer, Kurt Edsinger, Bo Cheng, Jeff Deshon, "An Integrated Approach to Maximizing Fuel Reliability," pp. 11-17.
[122] Id., p. 14.
[123] 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.[124] (Incidentally, during cycle 11, high temperatures caused significant fuel rod bowing in addition to fuel failures.)[125] 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, I estimate 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.)

3. 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

[124] 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.

[125] 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.[126]

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

[126] 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.[127] 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.

H. 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]."[128]

---

[127] 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.

[128] 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.[129]

After decades of operating experience, heavy crud and/or oxide layers on cladding or crud-induced corrosion failures remain within the realm of anticipated operational occurrences at nuclear power plants. 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.[130]

This EPRI document also refers to the "many operational surprises utilities have experienced recently"[131] at nuclear power plants, stating that among the operational surprises were "higher than expected [levels of] cladding corrosion and hydriding."[132] (I would add higher than expected levels of crud.) Meanwhile, in recent years, numerous power uprates and license renewals, largely based on non-conservative ECCS evaluation calculations (like those that helped qualify the recent power uprate of IP-2, discussed above), have been granted for nuclear power plants.

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

---

[129] Id.
[130] EPRI, "2006 Portfolio, 41.002 Fuel Reliability," p. 1.
[131] Id., p. 2.
[132] Id.

> disappeared in BWRs. Today's Zircaloy-2 cladding is essentially nodular corrosion free.[133]

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 as water rods and spacers could cause accelerated hydrogen absorption and concentrations in excess of 600 ppm.[134]

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.

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.[135] When discussing possible revisions to 10 C.F.R. § 50.46 at the same meeting, and at the NRC's

---

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

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

[135] 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.

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 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"[136] is being considered for regulation status for a new revised version of 10 C.F.R. § 50.46, due in 2009.[137]

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.[138] He also provided examples regarding cladding ductility where the value 1.2 (the F factor)[139] was multiplied by the pre-accident ECR in order to calculate the remaining percentage of oxidation allowed to occur during a LOCA.[140] 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."[141] (A NRC regulatory guide states that the F factor can vary from 1 to 1.6.[142] The F factor's use in LOCA calculations is also being considered for regulation status.)[143]

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

---

[136] NRC, "NRC Information Notice 98-29: Predicted Increase in Fuel Rod Cladding Oxidation."
[137] 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.
[138] NRC, Advisory Committee on Reactor Safeguards, Materials, Metallurgy, and Reactor Fuels Subcommittee Meeting Transcript, January 19, 2007, p. 13.
[139] Id., pp. 179-182.
[140] Id., pp. 31-33.
[141] Id., p. 31.
[142] Id., pp. 181-182.
[143] Id., p. 246.

> about [10%] ECR, and you multiply that by 1.2, subtract the 12 from 17, and you get five percent, a fairly small number."[144]

At the same 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.[145]

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].[146]

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 yield the highest PCTs,[147] 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[148]]. [A]nd [with high burnup fuel] you just [cannot reach temperatures that high].[149]

[144] Id., p. 33.
[145] Id., p. 243.
[146] Id., pp. 250-251.
[147] Id., p. 251.
[148] Id.
[149] Id., p. 261.

The conclusion to be drawn from Nissley's argument is that the F factor would only apply to cladding sheathing 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 loss of cladding ductility for properly managed high-burnup fuel in the event of a LOCA.[150]

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 substantially higher PCTs than the examples he cited. Furthermore, the cladding, in such scenarios, where there are crud-induced corrosion failures, would be substantially 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; however, there were also cladding perforations due to corrosion at TMI-1 Cycle 10, so its maximum ECR was actually 100% on one-cycle, high-powered fuel. The fuel at TMI-1 Cycle 10 (and any other nuclear power plant with crud-induced corrosion failures on one-cycle, high power fuel rods) would yield higher PCTs than fresh, BOL fuel; and this fuel was sheathed 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. It is imperative 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.

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

Respectfully submitted,

Mark Edward Leyse
P.O. Box 1314
New York, NY 10025
mel2005@columbia.edu

Dated: September 5, 2008