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73 FR 44778

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September 11, 2008

Mr. Michael T. Lesar
Chief, Rulemaking, Directives, and Editing Branch
Office of Administration
U.S. Nuclear Regulatory Commission
Mail Stop T6-D59
Washington, DC 20555-0001

Subject: Nuclear Industry Comments on the Technical Basis for New Performance-Based Emergency Core Cooling System Requirements

Project Number: 689

Dear Mr. Lesar:

In early 2003, the Commission directed the NRC staff to complete the technical basis and move forward with rulemaking to establish improved, performance-based ECCS acceptance criteria in 10 CFR Section 50.46(b), "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors." Since 1998 the NRC has sponsored a research and testing program at Argonne National Laboratory (ANL) to develop the body of technical information needed to support the new regulations. This information has been summarized in RIL-0801 ("Technical Basis for Revision of Embrittlement Criteria in 10CFR50.46") and the detailed experimental results are contained in NUREG/CR-6967 ("Cladding Embrittlement During Postulated Loss-of-Coolant Accidents").

On July 31, 2008, the Federal Register published for comment the technical basis for new performance-based Emergency Core Cooling System requirements (73 FR 44778). This letter submits a consensus of the nuclear industry's comments in response to 73 FR 44778. The Federal Register solicitation identified three broad areas for comment, with detailed areas under each aspect. For clarity, the enclosure restates each of these areas and provides detail comments. The following paragraphs summarize some of the industry's main comments on this subject.

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P. Clifford (PMC3)

The NRC-RES confirmatory research program at ANL has been able to confirm the Cathcart-Pawel (CP) best estimate correlation for cladding oxidation kinetics. They have also confirmed the Hobson's ring compression test results ($\geq$17% ECR) on unirradiated cladding samples oxidized at approximately 1200°C and subjected to ring compression tests at 135°C. In addition to ring compression tests, NRC-RES sponsored three LOCA integral tests on BWR samples extracted from rods irradiated at Limerick to burnup levels in excess of 55 GWd/MTU. They determined from these tests that irradiated Zr-2 cladding balloon and burst characteristics are very similar to unirradiated cladding performance. The oxidation kinetics and embrittlement are also similar between irradiated and unirradiated, pre-hydrided samples.

The new experimental results do not indicate a significant safety issue that would need to be addressed immediately by revision of the ECCS acceptance criteria. Recent research performed in both the US and Japan have confirmed that high burnup fuel can survive LOCA-like thermal shock quench events up to and exceeding the current cladding high temperature oxidation limits specified in 10 CFR 50.46. In addition, the peak cladding temperature (PCT) of high burnup UO2 fuel remains well below current limit temperature of 1200°C without lower burnup fuel violating the limits.

The successes demonstrated at ANL are encouraging. The information presented in NUREG/CR-6967 has helped in the understanding of burnup effects on cladding behavior during and after a LOCA event; however, the technical information provided in NUREG/CR-6967 is incomplete and not yet sufficient to justify the regulatory criteria proposed in RIL-0801.

The nuclear industry appreciates the opportunity to provide comment on the technical basis for the proposed regulations and looks forward to working with the NRC staff on this issue. If you have any questions, please do not hesitate to contact me at (202) 739-8137; jhr@nei.org or Gordon Clefton at (202) 739-8086; gac@nei.org.

Sincerely,

James H. Riley

James H. Riley

Enclosure

c: Mr. William H. Ruland, NRR/ADES/DSS, NRC
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Comments on the Adequacy of Technical Information in RIL-0801 and NUREG/CR-6967 Requested in Federal Register Notice

I. Technical Basis

1. *RIL 0801 Figure 1 provides the measured embrittlement threshold for all fresh and irradiated cladding specimens investigated during the ANL research program. Hydrogen dependent post-quench ductility regulatory criteria, similar to the lines on this figure, may be established from these experimental results.*

    a. *Is the technical information presented within NUREG/CR-6967 sufficient in scope and depth to justify specific regulatory criteria applicable to all current zirconium cladding alloys?*

The technical information presented in NUREG/CR-6967 falls into three main categories; ballooning and burst, high temperature oxidation behavior, and post-quench ductility (PQD). ANL has reported some PQD and breakaway oxidation test results for unirradiated and irradiated cladding alloys provided by GNF (8×8, 9×9 and 10×10 Zry-2), Westinghouse (17×17 low-tin Zry-4 and ZIRLO), AREVA (1970's 15×15 Zry-4 tubing, 1990's 15×15 low-tin Zry-4, 15×15 Zry-4, 15×15 M5, and 17×17 M5) and Fortum (E110 tubing and E110 cladding). For the advanced-alloy post-quench ductility tests, the primary alloys of interest were 17×17 ZIRLO and 17×17 M5. Integral LOCA test results for irradiated BWR fuel segments were also reported.

Many of the ANL observations from ring compression tests are not consistent with results obtained by overseas facilities (see response to I.2.b). These differences have been attributed to the applied temperature profile and the quench rate and initiating temperature. The range of the test variables used in the ANL program was limited and is not sufficient to understand these effects. More data is needed to define the interaction between the transient temperature profile, temperature at which quench occurs and hydrogen content on the cladding microstructure.

The PQD database on Zr-2 material is also sparse. Not enough testing was performed on either pre-hydrided or irradiated Zr-2 cladding material to define the Zr-2 material performance with increasing hydrogen content. The lack of experimental data to support a hydrogen vs. ECR embrittlement curve may result in undue conservatism being applied to Zr-2 material during the rule-making process. Therefore, additional testing needs to be done with hydrogen-charged samples simulating high burnup fuel.

In addition, due to a change of status at the ANL hot cells, testing on irradiated fuel rods has been halted. While that planned work has been shifted to Oak Ridge National Laboratory, the schedule for the restart of that work is not available. Thus important integral tests planned for irradiated PWR fuel have not been conducted. This includes a planned test of a pressurized sealed fuel rod section to investigate the inner cladding surface oxygen uptake behavior to evaluate the validity of the double-sided oxidation requirement specified in RIL-0801. The test segment will be pressurized and run through a LOCA temperature ramp without ballooning and burst in order to determine the amount (if any) of alpha phase formation on the inner cladding surface and oxygen ingress into the prior beta phase due to the fuel/clad bonding layer.

The Industry considers the unfinished LOCA integral tests to be of importance in order to quantify the effects of the fuel-clad bonding layer on the overall cladding ductility response. A conclusion drawn from the ANL program and stressed in the RIL is that there is a need to account for oxygen uptake at the cladding inner surface away from the ballooned region by requiring the assumption of double-sided oxidation in these regions. This conclusion was largely based on data obtained from single-sided oxidation tests performed at ANL. RIL-0801 referenced recent micrographs from Halden test IFA-650.5 which appears to show some formation of an ID alpha layer away from the ballooned region in the case of a fuel specimen irradiated to burnup levels of ~ 83 GWd/MTU, well beyond the currently licensed (or practical) limits. However, the observed oxygen stabilized alpha phase was only in the order of ~25 micrometer in thickness which could have also formed from pre-existing oxide layer or fission released free oxygen.

Doubling the transient oxidation may exaggerate the effect of ID oxygen uptake. It assumes that the amount of oxygen uptake is same from outer surface steam oxidation and ID oxide layer reduction. In order for this to occur there needs to be strong pellet-clad contact/bonding for the additional oxygen source to be available. It is not clear to what extent this applies to a LOCA event. Data suggests a potential of ID alpha layer growth from pre-existing ID oxide layer. However, there is only a limited oxygen source from the inner-surface bonding layer (confirmed by the Limerick Zr-2 oxidation tests). Results from the ANL integral tests on Limerick fuel samples do not confirm the need for the added conservatism. There is no consistent, clear indication of inner surface oxygen uptake beyond the balloon region.

In summary, the technical information provided in NUREG/CR-6967 is incomplete and not yet sufficient to justify the regulatory criteria proposed in RIL-0801.

b. Is the technical information presented within NUREG/CR-6967 sufficient in scope and depth to justify periodic testing on as-fabricated cladding material?

The information presented in NUREG/CR-6967 does not adequately demonstrate a need for periodic testing for PQD and breakaway oxidation on as-fabricated cladding material. The concerns arise from the potential of manufacturing variability on PQD and potential trace elements effects on breakaway oxidation. Both concerns are not well supported when ANL test data reported in NUREG/CR-6967 are taken into consideration collectively.

Manufacturing variability concern results from the testing of different as-fabricated Zry-4 lots (as shown in NUREG/CR-6967 Figure 28) supplied to the ANL program. Variation in the results is no longer observable in the hydrided state (NUREG/CR-6967 Figure 120 and NUREG/CR-6967 page 171) within the context of the tests performed. NUREG/CR-6967 Figure 120 also suggests the embrittlement CP-ECR is not sensitive to manufacturing variability under the test condition used by ANL. Since the hydrogen content is the figure of merit for PQD performance used in RIL-0801, the technical information presented in NUREG/CR-6967 does not support the need to perform periodic testing for PQD on as-fabricated cladding.

Most of the testing on the effects of trace element variations on clad performance was associated with breakaway oxidation tests on E110, a Russian alloy. The trace element concern appears to come from the comparison of breakaway oxidation tests performed on M5 and E110. The fabrication process of E110 uses zircon ore refined using an electrolytic process, compared to western manufacturers' use of the Kroll refining process. The ANL data shows that E110 performance is strongly affected by surface condition and significant improvement was found with substantial surface removal (NUREG/CR-6967 Figure 94).

Trace element concern arises because E110 still performed worse than M5 after ANL's machine-and-polish treatment (NUREG/CR-6967 Figure 98, machine-and-polish on ID and polish only on OD). Polishing alone was shown to be only partially effective in improving oxidation performance as shown by ANL tests results (NUREG/CR-6967 Figure 97). The benefit of machining-and-polishing over simply polishing is demonstrated in NUREG/CR-6967 Figure 96, where incipient local white oxide may have started to appear on the polished only section and not on the larger machined-and-polished section. However, tests on western alloys using the Kroll process show little variation in regards to trace elements and surface finish. Therefore, the limited scope of the ANL tests on western alloys does not appear to support the need to perform periodic testing for breakaway oxidation on as-fabricated cladding.

The technical information presented in NUREG/CR-6967 did however confirm the Cathcart-Pawel (CP) best estimate correlation for cladding oxidation kinetics. They have also confirmed the Hobson's ring compression test results (≥17 % ECR) on unirradiated cladding samples oxidized at approximately 1200°C and subjected to ring compression tests at 135°C.

> *c. Is the technical information presented within NUREG/CR-6967 sufficient in scope and depth to address sensitivities to alloy composition, trace elements, manufacturing practices, fuel rod burnup, and transient temperature profile?*

The ANL program included all the current alloy types used in fabricating fuel rod cladding. Tests performed at ANL included both ductility testing and breakaway oxidation studies.

In regards to the effect that alloy composition, trace elements and manufacturing practices has on ductility, the proposed hydrogen dependent PQD criterion is based on a limited amount of data from irradiated Zry-4, M5 and Zirlo (NUREG/CR-6967 Figures 237 and 238) and from unirradiated Zry-4, M5, Zirlo and Zry-2 tubing that was processed from multiple suppliers. The combined use of data from different vendors indicates that ductility does not appear to be a direct function of alloy composition, trace element or manufacturing practices (see also response to I.1.b). Given the test conditions used in the ANL program, the technical information presented NUREG/CR-6967 is sufficient to show no alloy composition, trace elements and manufacturing practices effects on ductility.

The major sensitivity for alloy composition, trace elements and manufacturing practices was highlighted in the breakaway oxidation studies. ANL used different tubing material fabricated from multiple suppliers in the test program. Sensitivity to manufacturing process and surface finish was found in E110 (electrolytic process) which has a much shorter breakaway oxidation time compared to western alloys (Kroll process). The technical information in NUREG/CR-6967 appears to be adequate to determine sensitivities to surface conditions but inconclusive on trace elements for breakaway oxidation.

It should be noted that breakaway oxidation is an instability phenomenon that may be sensitive to sample preparation and test conditions. There have been differences in results between ANL and other laboratories. In order to standardize such testing, additional tests should be conducted to determine the sensitivity of results to sample length and cleaning, steam flow rates, heating ramp rate and method, and circumferential temperature variation. It is recommended that these differences be evaluated before breakaway oxidation tests are standardized.

The ANL program determined that the fuel burnup effect of most importance is the hydrogen content of the cladding. For a fuel cladding fabricated from a Zr-based alloy, there are three types of metallurgical processes that can lead to large hydrogen uptakes:

1. Fractional hydrogen uptake as part of the outer surface waterside corrosion reaction during normal operation to high burnup.
2. Rapid hydrogen permeation through either an unprotected oxide free surface or cracked oxide layer that may form on the cladding inner surface near a burst opening when the surface is exposed to hydrogen rich mixture of steam-hydrogen gas during the LOCA transient (secondary hydriding).
3. Accelerated hydrogen permeation through cracked breakaway oxide that can form in steam at high temperatures on the cladding outer surface after extended oxidation times (accelerated hydrogen pickup during breakaway oxidation).

The technical information presented within NUREG/CR-6967 is sufficient in scope and depth to identify that hydrogen accumulated during the burnup process has the largest impact on the cladding ductility. However the limited number of tests conducted does not provide sufficient information to determine the sensitivity of cladding ductility to hydrogen over a wide range of temperature profiles and quench rates.

Another burnup related phenomena identified in RIL-0801 and supported by NUREG/CR-6967 is a potential need to account for some oxygen uptake at the cladding inner surface away from the ballooned region beyond some level of burnup. RIL-0801 specifies the use of the CP-model at the cladding ID as a means to account for the oxygen uptake throughout the entire high temperature oxidation period of the accident. By requiring the assumption of double-sided oxidation in these regions (see discussion in response to I.1.a), RIL-0801 is in effect assuming an unlimited supply of oxygen at the cladding inner surface. The technical information provided in NUREG/CR-6967 is not sufficient to support this assumption. More data is needed to resolve this issue.

In regards to the transient temperature profile, not all of the prior beta phase is equally strong or ductile since these properties depend on the amount of dissolved oxygen in the material matrix. As a result of the diffusion process, there is a greater incursion of oxygen into the beta phase and stabilized alpha phase at higher temperatures since the diffusion rate and oxygen solubility depend exponentially upon temperature. Hydrogen influences the prior beta phase by increasing the oxygen solubility by possibly stabling the beta phase to lower temperatures. It also forms zirconium-hydrides in the prior-beta phase which impacts ductility after quench.

Therefore, the key parameters for ductility measurements are the heating/cooling/quench temperature profile and how those affect the oxygen dissolved in the prior-beta phase and hydrogen content. As discussed in the answer to I.2.b, many of the ANL observations are not consistent with results obtained by overseas facilities. These differences are a function of the applied temperature profile and the quench initiating temperature. The technical information presented in NUREG/CR-6967 is not sufficient to understand the effects of temperature profile and quench on ductility. ANL data should be considered preliminary until the understanding of the interaction between the temperature profile, quench rate and hydrogen content is better understood.

2. *Section 2 of NUREG/CR-6967 details the experimental techniques and procedures employed at ANL to assess cladding properties.*
    a. *Were the experimental techniques and procedures adequate for their intended purpose of defining acceptable fuel criteria (e.g., specimen preparation, specimen size, heating/cooling rates, ring-compression techniques, test temperature, acceptance criteria for post-quench ductility and breakaway oxidation, etc.)?*

The ANL program applied a series of experimental techniques to investigate ductility and breakaway oxidation. The information presented in NUREG/CR-6967 has helped in the understanding of burnup effects on cladding behavior during and after a LOCA event. However, there is too much uncertainty associated with the ANL experimental techniques and procedures to conclude that the results are adequate for rule making. ANL observations from ring compression tests are not consistent with results obtained by overseas facilities (see response to I.2.b). These differences have been attributed to the applied temperature profile and the quench initiating temperature. The range of the test variables used in the ANL program was limited and is not sufficient to understand these effects. A well established set of experimental procedures need to be developed such that independent laboratories can produce consistent results for a given alloy.

Similarly, there have been differences in results on breakaway oxidation studies between ANL and other laboratories. In order to standardize such testing, additional tests should be conducted to determine the sensitivity of results to sample length and cleaning, steam flow rates, heating ramp rate and method, and circumferential temperature variation. It is recommended that these differences be evaluated before breakaway oxidation tests are standardized.

b. *Is the technical information presented within NUREG/CR-6967 sufficient in scope and depth to address uncertainties related to and repeatability of measured results?*

The ANL program combines separate effects tests and integral tests to evaluate the impact of burnup on fuel rod behavior during a LOCA. However, many of the ANL observations on prehydrided and irradiated samples are not consistent with results obtained at overseas facilities such as CEA/EDF/Framatome (France). Figures 1 highlights some of the differences in the ductility data for samples with a hydrogen content of approximately 600 wppm that have been oxidized at 1200°C.

There are lab-to-lab differences in the sample preparation that can contribute to differences in ductility measurements. First, there is no "typical" LOCA temperature history applied by all experimentalists during the sample oxidation process. The temperature history used to oxidize and cool the samples plays a key role in the eventual sample ductility. ANL has a fast initial ramp followed by a slow approach to the final oxidation temperature to avoid a temperature overshoot. CEA has a direct ramp to temperature without overshoot. The ANL heating method is presented in Figure 2 and results in less total oxidation at target temperature (i.e. 1204°C). The CP-predicted ECR values have been placed on Figure 2 temperature history in order to demonstrate the effect on ECR accumulation associated with the non-isothermal oxidation process used by ANL. (The ANL samples accumulate ~5% ECR before even reaching the target limiting temperature. Actual LOCA scenarios would accumulate even more ECR before approaching the temperature acceptance criterion.)

Second, the cooldown from oxidation temperature also contributes to the sample ductility. ANL furnace cools most of their samples compared to the CEA tests that are mostly quenched directly from the oxidation temperature. The direct quench study is of scientific value as it is useful in developing an overall understanding of the material behavior during cooling but it does not represent a realistic LOCA scenario. A third effect is the temperature at which quench occurs. The heating rate, cooling rate, and quench temperature all have an impact on the prior-beta and hydride morphology in the beta phase.

The differences in heating rates can account for some of the variation seen between laboratories conducting ductility studies. Differences in cooling rates and differences in quench temperature (or lack of quench) also add additional uncertainty in the database. How these testing differences affect the interplay between hydrogen and oxygen and the eventual sample ductility is not yet fully understood.

As was discussed previously, breakaway oxidation is an instability phenomenon that is very sensitive to sample preparation and test conditions. As with the ductility measurements, there have been variations in results between ANL and other laboratories. ANL has not adequately defined the uncertainty associated with the breakaway oxidation tests. Additional tests should be conducted to determine the sensitivity of results to sample length and cleaning, steam flow rates, heating ramp rate and method, and circumferential temperature variation. It is recommended that these differences be evaluated before breakaway oxidation tests are standardized.

Thus, we have to conclude that the technical information presented in NUREG/CR-6967 is not sufficient in scope and depth to address the uncertainties related to the measured results.

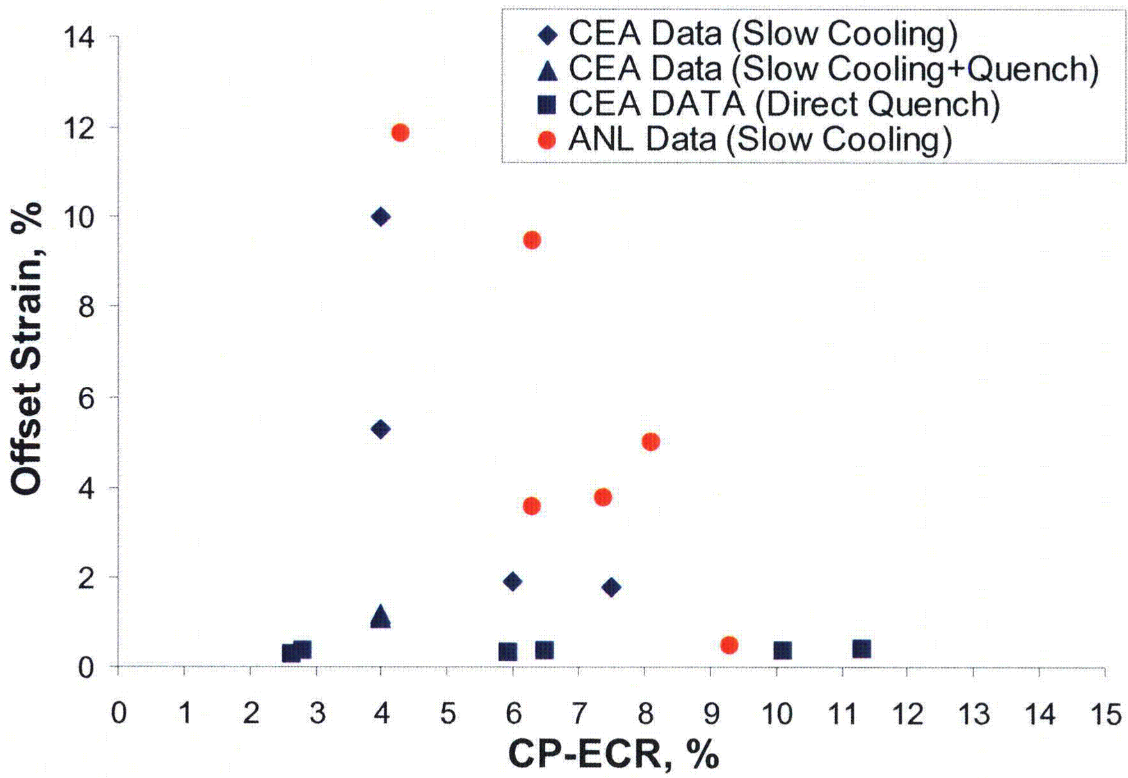

Figure 1. Comparison of ANL & CEA Post-Oxidation Ductility Offset Strain vs. CP-ECR. Samples were oxidized at 1200°C and have a hydrogen content of approximately 600 wppm.

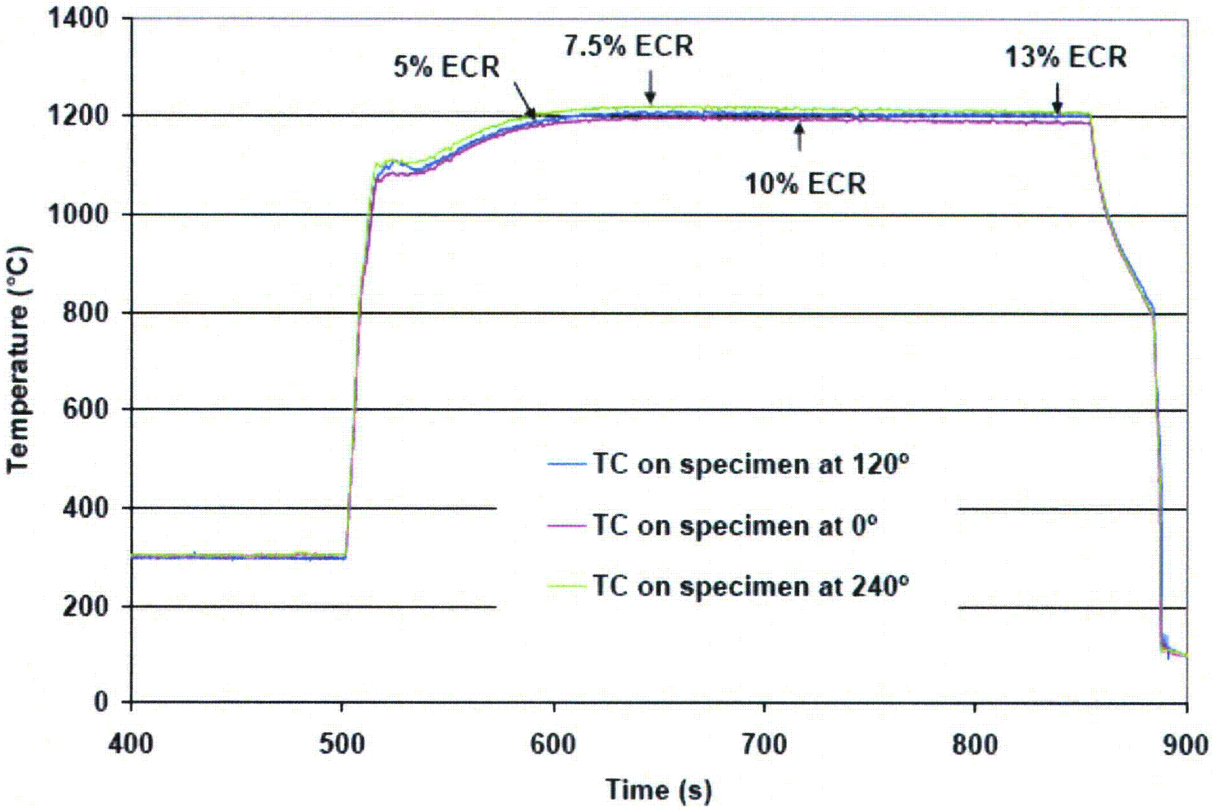

Figure 2. Thermal benchmark results from two tests, each with two thermocouples welded onto as-fabricated, HBR-type 15×15 Zry-4 cladding.

II. Performance-Based Testing Requirements

1. *Due to potential sensitivities to manufacturing processes, performance based testing may be required to characterize the loss-of-coolant accident (LOCA) performance of new cladding alloys.*
   a. *Section 2.1 of NUREG/CR-6967 details all of the fresh and irradiated cladding specimens investigated during the ANL research program. Is the extent of the ANL material database sufficient to justify the applicability of experimental results to future cladding alloys?*

The basic form of the test methodology and insight gained from the ANL program to investigate cladding ductility and breakaway oxidation would be applicable to future cladding alloys. However, the ANL results for the various cladding alloys may or may not bound future alloy performance. The key parameters for ductility are the hydrogen pickup rate of the cladding alloy and the expected transient temperature profile and quench initiation temperature used in the oxidation test. For breakaway oxidation studies, the sample preparation and heating method are among the important parameters to standardize.

   b. *Conducting testing on irradiated specimens is more difficult and expensive than similar tests performed on unirradiated specimens. Does a sufficient technical basis exist to justify testing on hydrogen charged, unirradiated cladding specimens as a surrogate for irradiated fuel cladding?*

Irradiation to high fuel burnups can affect the cladding ability to survive the quenching process. During irradiation, cladding surface oxidation can accrue, depending on the alloy, to reasonably significant levels. This low temperature oxidation allows for the buildup of hydrogen within the cladding but does not lead to the development of a thick oxygen stabilized alpha layer. Embrittlement of high burn-up cladding arising from the high-temperature transient during a LOCA event requires both high hydrogen and high oxygen within the cladding. Irradiation damage, another source of embrittlement, is annealed out during the high temperatures produced during the LOCA transient and therefore has no effect on post-quench cladding ductility. Based on these observations, the hydrogen content of the cladding is the primary factor produced by irradiation that may affect cladding embrittlement during high temperature oxidation. Therefore, the use of pre-hydrided cladding is an adequate surrogate for irradiated cladding.

A review of ANL data that was oxidized at 1200°C and slow cooled to room temperature is presented in Figure 3 and shows that the behavior of irradiated cladding and pre-hydrided cladding is similar. Thus we can conclude that there is sufficient technical basis to justify testing on unirradiated, hydrogen charged surrogate specimens.

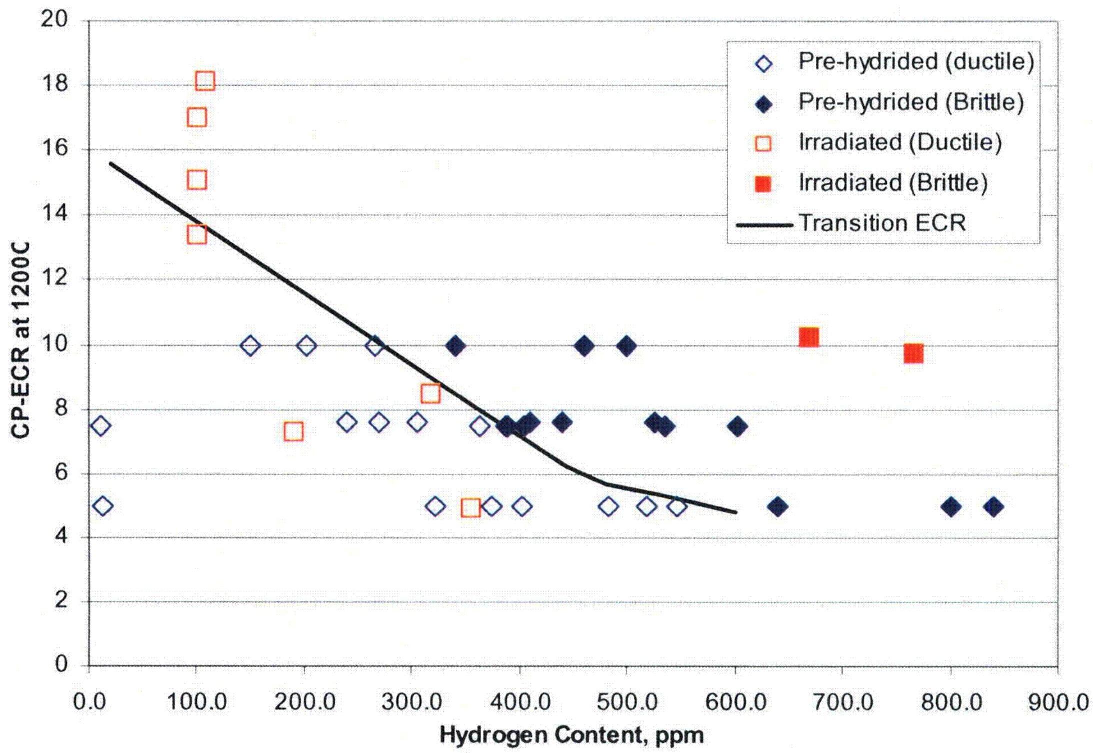

Figure 3. Comparison of ANL data (irradiated and pre-hydrided)

2. *Due to potential sensitivities to manufacturing processes, routine testing may be required to verify material performance. Are there difficulties or limitations with periodic testing that would make such a requirement impractical?*

Cladding manufactures have quality control programs in place to assure product specifications. The technical information presented in NUREG/CR-6967 does not support the need for periodic testing of as-fabricated material (see discussion in response to I.1.b).

III. Implementation

1. *Implementing new regulatory criteria for 10 CFR 50.46(b) may necessitate further testing and new licensing activities (e.g., revised methods, updated safety analyses, etc.). What is the cost-benefit for implementing new regulatory requirements similar to those discussed in RIL 0801?*

The ANL test program has provided much information on the effects of burnup and hydrogen on clad performance during a hypothetical LOCA event. However the testing has been carried out for only a limited number of test conditions. Furthermore, repeatability is questionable for some of the tests conducted. In order to implement a new rule, a more comprehensive database would need to be constructed using both hydrogen-charged and irradiated material over a range of burnups. Testing on hydrogen-charged samples could cost on the order of one million dollars. Hot cell testing on irradiated material would be much more expensive, likely by an order of magnitude. The total cost to develop a more robust database is estimated to be on the order of tens of millions of dollars per vendor per alloy.

Corrosion and hydrogen models would require refinement and approval for LOCA licensing. A high cost impact is expected since hot cell investigations will likely be required to generate the data needed to gain approval of these models. There will also be cost impact in establishing and maintaining test facilities for pre-hydriding, oxidation, post-oxidation characterization, and for RCT. Depending on the final ruling, the embrittling ECR curve for prehydrided Zry-2 may need to be generated and may involve testing of irradiated cladding. Again depending on the final ruling, the cost impact could be on a one-time or a continual basis. ANL results suggest that potential ductility variation due to manufacturing variability is not reflected in hydrided state, representing in-service condition (NUREG/CR-6967 Figure 120). Periodic testing will incur additional carrying costs with little, if any, benefits that address primarily surface contamination and surface roughness. Surface conditions are typically addressed by quality control measures that are already in place.

In addition, there will be a large cost associated with modifying LOCA evaluation models to demonstrate compliance with the new rule. All LOCA evaluation models currently in use will need to be modified, and re- submitted for NRC review so that the design basis licensing analyses are consistent with the new requirements. A significant fraction of the reactors currently licensed for operation in the US will have new small break/large break analyses performed by their fuel vendor, submit Licensing Amendment Requests to revise their licensing basis analyses, update their latest Safety Analysis Reports, and respond to any USNRC Requests for Additional Information arising from this process.

In summary, the cost to fully implement the new rule could be on the order of hundreds of millions of dollars with no real gain in safety.

2. *Implementing hydrogen-based regulatory criteria may require the development of high confidence corrosion and hydrogen pickup models.*
    a. *What type of information is needed to develop such models and is such information readily available?*

Since hydrogen is generated in the oxidation process, a model correlating hydrogen pickup up to cladding oxidation will need to be developed. A database of clad oxide thickness over a range of burnup, fuel duty, and coolant chemistry conditions will have to be created to support this effort.

Poolside inspection techniques are available for assessing cladding corrosion layer thickness. However, the presence of crud could make the measured oxide thickness unreliable. A direct correlation to cladding hydrogen concentration is not always achievable for BWR cladding. In the case of Zry-4, the hydrogen pickup fraction is relatively constant and oxide thickness could be used as a surrogate for hydrogen. For Zry-2 typically used in BWRs, the cladding hydrogen content cannot be readily deduced from oxide thickness and hot cell examination is currently required to get hydrogen data.

b. What performance indicators (e.g., pool-side measurements, hot cell examinations, etc.) could be used to validate models?

Oxide thickness data from poolside eddy current (EC) measurements are the most useful indicators of clad corrosion performance in PWRs. The data can be obtained relatively quickly and can provide feedback on corrosion performance within a month of the end of a cycle of irradiation. Limited hot cell metallography measurements confirm the accuracy of EC measurements. Hot cell results typically take much longer to obtain (over 2 years after completion of irradiation) than poolside exams, so poolside EC measurements are preferable as a timely indicator of in-core clad corrosion performance.

For BWRs, hot cell examination seems inevitable until improved pool-side techniques become available.

c. What additional regulatory requirements would be necessary to assure that the fuel is performing in accordance with the approved models? How will compliance with the rule be demonstrated on a cycle by cycle basis?

Additional regulatory requirements will not benefit the public health and safety. A design evaluation on oxide thickness can address the impact of hydrogen through licensed hydrogen pickup models. Using this approach, the normal corrosion analysis typically performed as part of the reload analysis is sufficient to demonstrate compliance on a cycle-by-cycle basis.

3. 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 perspective?

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. However, 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 insure that the cladding does not exceed the mechanical design limits e.g. design stress and design strain.

For those PWR cases in which unusual crud patterns and deposits were observed, post-cycle fuel inspection has shown that there was no significant increase in over-all cladding corrosion compared to existing approved corrosion models and therefore the cladding temperature was unaffected by the presence of the crud, with the exception of a very limited number of localized damage sites. These localized damage sites are limited both axially and azimuthally such that their thermal resistance effect on the overall fuel temperature and stored energy is small. Crud-affected fuel rods are not expected to have any significant effects on initial core conditions that could affect LOCA and any impact on LOCA analyses would be negligible.

For the BWR cases, significant increases in cladding corrosion have only been observed in conjunction with unusually heavy tenacious crud formation. Such crud formation occurred only at lower elevations and thus would have had an impact on the initial stored energy in the fuel only for these locations. Whereas it is true that flow through the affected bundles would be reduced leading to higher initial voiding in the upper part of these bundles, this effect is of secondary importance for a postulated LOCA and is within the envelope determined for core operations with reduced core flow. The calculated PCT in a BWR LOCA event is relatively insensitive to the initial stored energy because PCT values that can challenge the licensing limit occur later in the event and are dominated by the balance between the decay heat and the amount of steam cooling after the initial stored energy difference has been mitigated. It is true that a very early peak in the calculated PCT is sensitive to stored energy but this value is seldom the most limiting value and when it is, it is far from the licensing limit of 2200 °F.

An example of a BWR analysis that demonstrates the potential effect of crud is presented in Figure 4. This analysis compares the PCT response of a typical fuel rod during a normal LOCA transient to the same fuel rod with the addition of crud. A conservative value for the thermal conductivity of the crud is assumed in the analysis. The analysis demonstrates that the principal result of the crud addition is to increase the initial calculated PCT and early peak temperature. Once the initial stored energy is mitigated, crud no longer has a great effect on PCT. This behavior is also typical of PWR fuel rod response.

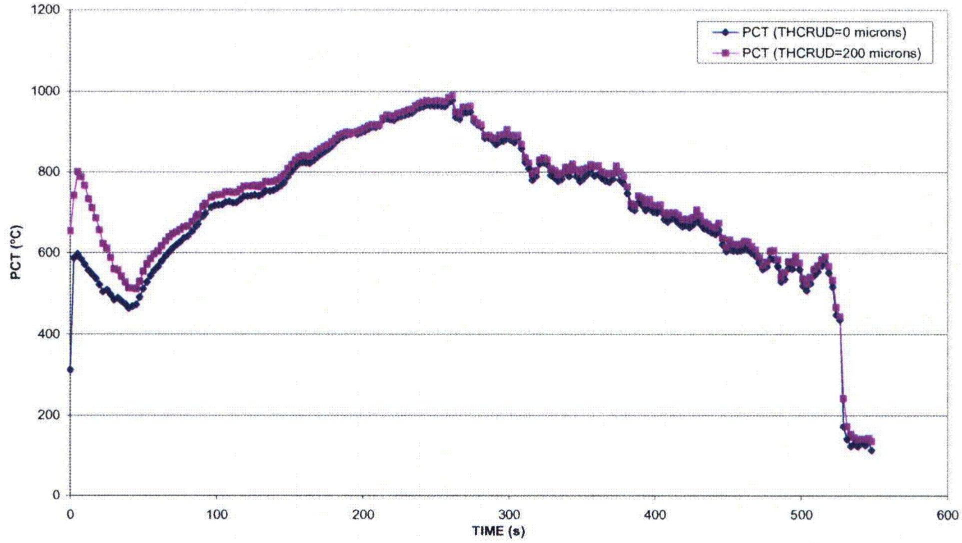

Figure 4. GE-14 Fuel Design Calculated PCT Response to a typical LOCA Event with and without Crud

Conclusion

The information presented in NUREG/CR-6967 has helped in the understanding of burnup effects on cladding behavior during and after a LOCA event. However, the technical information provided in NUREG/CR-6967 is incomplete and not yet sufficient to justify the regulatory criteria proposed in RIL0801. The ANL data should be considered preliminary until additional testing is performed and the issues are resolved. Among these are: results from integral tests on high-burnup PWR rods from HB Robinson, more results on pre-hydrided Zr-2 cladding, and addressing the concerns associated with the testing techniques.

The concept of LOCA criteria has evolved as NRC-RES and ANL have learned from the ongoing LOCA testing. This has made it difficult for Industry to evaluate and propose alternate criteria. Now that RIL0801 and NUREG/CR-6967 have been issued, Industry needs the time to evaluate, perform testing as needed and present alternatives.