May 18, 2001

Lynette Hendricks
Director, Licensing
Nuclear Energy Institute
Suite 400
1776 I Street, N.W.
Washington, DC 20006-3708

SUBJECT: REQUEST FOR ADDITIONAL INFORMATION (RAI) REGARDING HIGH BURNUP FUEL CHARACTERISTICS

Dear Ms. Hendricks:

On April 18, 2001, staff from the Spent Fuel Project Management Office (SFPO) met with staff from the Nuclear Energy Institute (NEI), the Electric Power Research Institute (EPRI) and industry representatives to discuss two recent NEI reports concerning the characteristics of high burnup fuel. These reports are intended to provide input to the staff's development of revised guidance for approval of cask designs for the storage of high burnup fuel. During that meeting, the SFPO staff stated that it would provide a set of questions to NEI based on its review of the two reports and consideration of other issues related to the storage of high burnup fuel. Accordingly, enclosed is the Request for Additional Information which addresses the subjects of creep and fracture toughness.

We recognize there is insufficient data at this time to address all of the technical issues related to storage and transportation of high burnup fuel based on the current creep and fracture mechanics approach. Therefore, it may be beneficial to consider using a more risk informed approach consisting of a risk assessment and risk management plan. In this regard, the Department of Energy has information on the likelihood and consequences of spent fuel cladding failure from the Yucca Mountain performance assessment that may be useful to address the issues associated with storage and transportation of high burnup fuel.

After NEI and EPRI staffs have reviewed the questions, I suggest that we have a conference call to discuss your schedule for providing responses to the questions. Additionally, I suggest that we identify potential dates for future meetings to discuss alternative risk assessment analyses which could support the long term experimental programs.

We appreciate your efforts to date on this difficult high priority issue and look forward to continued interaction with you.

Sincerely,

/RA/

M. Wayne Hodges, Deputy Director
Technical Review Directorate
Spent Fuel Project Office
Office of Nuclear Material Safety
and Safeguards

Enclosure: Request for Additional Information

We appreciate your efforts to date on this difficult high priority issue and look forward to continued interaction with you.

Sincerely,

(Original Signed by:)

M. Wayne Hodges, Deputy Director
Technical Review Directorate
Spent Fuel Project Office
Office of Nuclear Material Safety
and Safeguards

Enclosure: Request for Additional Information

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REQUEST FOR ADDITIONAL INFORMATION

10 CFR 72.122(h)(1) requires that spent fuel cladding must be protected from degradation that leads to gross rupture, or the fuel must otherwise be confined so that degradation of the cladding will not impose operational safety problems. Further, 10 CFR 72.122(l) requires that the storage system must be designed to allow ready retrieval of the spent fuel from the storage system for further processing or disposal. Consistent with these regulations, provide the responses to the following questions.

A. General

1. Using appropriate stress analyses that model normal handling operations, demonstrate that high burnup fuel assemblies can be retrieved intact from the storage cask system or Independent Spent Fuel Storage Installation at the end of the licensing period. In the response, include the effects of creep damage and any potential wall thinning that could occur during the licensing period. Evaluate the likelihood and consequences of potential fuel cladding failure during retrieval operations of the fuel from the storage cask. The analysis should assume that the failed high burnup fuel redistributes in a credible, but bounding configuration.

B. EPRI Report 1001207, “Creep As The Limiting Mechanism For Spent Fuel Dry Storage”, December 2000.

1. The report outlines an approach that establishes a creep strain limit. Describe the methodology that a licensee would use to derive a temperature limit, or other licensee/cask vendor controllable limit from the proposed creep strain limit, that would demonstrate that 10 CFR 72 regulations are met. Provide example predictions of peak fuel cladding temperature limits for high burnup fuel at the limiting stresses. Also, provide the corresponding creep strain predictions.

2. The report concludes that stresses in excess of 138 MPa and several thermal cycles are needed to obtain significant hydrogen reorientation to cause delayed hydride cracking of spent fuel during dry storage. Justify how the data of Louthan and Marshall (1963), Hindle and Slattery (1971), Ells (1968) and Pickman (1972), and Einzinger and Kohli (1984) support this conclusion.

3. The report claims that the high burnup and highly oxidized/hydrided (and spalled) zircaloy has sufficient fracture toughness to withstand crack propagation. Justify that the fracture toughness values (used in the calculations) are applicable to highly oxidized zircaloy cladding (including spalled cladding) that is typical of highly burned fuel.

4. Provide the justification for selecting the critical strain energy density (CSED) approach as a method to predict the fracture toughness of zircaloy cladding of high burnup fuel. In the absence of data, a discussion of the applicability of this method to materials with conditions similar to zircaloy clad high burnup fuel and a comparison of appropriate data to modelling predictions should be provided.

5. One of the major conclusions of the report is that "sufficient data and analytical modeling exist to show that a strain limit of 2% can be safely used as an asymptotic limit for fuel rods normally discharged from reactors without imposing any restrictions on oxide thickness or physical conditions." Provide a discussion, citing references, that describes the data and assumptions that were used to support the 2% strain limit for prototypical high burnup fuel experiencing the stress and temperature ranges expected under dry storage conditions. The expected cladding temperature and stress ranges where creep is expected to be the dominant deformation mechanism under dry cask storage conditions are 300-400 °C and 50-150 MPa, respectively. The expected oxide thickness and average hydrogen concentration of high burnup fuel are in the range of 50-130 micrometers and 300-900 parts per million, respectively for non-spalled rods.

6. Justify the use of total strain (versus uniform strain) to adequately predict, and provide sufficient margin for, the expected failure mode(s) of high burnup fuel cladding under expected dry cask storage conditions. If the NEI/EPRI approach utilizes the total strain as the basis for a strain limit, as proposed in the subject report, describe how the proposed methodology (a) differentiates the strain observed in tensile tests from the strain observed in creep tests, (b) is related to creep phenomena, and (c) uses extrapolation of tensile (residual) strain data to creep strain limit considers the effect of potentially adverse localized cladding microstructural features (such as hydride lenses).

7. The last paragraph on pages 5-1 states that, "This demonstrates that in the event of fracture, the crack will propagate slowly in a self-similar manner.......before it can extend axially in a burst mode. The above calculations are valid for all cladding conditions regardless of oxide thickness or the state of the oxide, coherent or spalled." Justify that the velocity of the pressure wave is greater than the velocity of the crack. Additionally, since there are limited data applicable to high burnup fuel under dry cask storage conditions, describe the uncertainties associated with both the selection of the pin-hole-equivalent mode of failure and the fracture toughness data that were used to perform the calculations.

C. <u>EPRI Report 1001281, "Fracture Toughness Data for Zirconium Alloys -- Application to Spent Fuel Cladding in Dry Storage," January 2001</u>

1. The derived CSED values account for the sum of both crack initiation and crack propagation K values. However, the threshold fracture toughness (K) values for various mechanisms, such as DHC for example, utilize the threshold crack initiation values for K. Please justify the use of CSED-derived K-values for fracture mechanism considerations.

2. The submittal considers an approach relating a critical strain energy density (CSED) value for any material to the corresponding fracture toughness for the material. Essentially, the CSED is equated to the integrated stress-strain area in a mechanical strength test. The CSED values and associated estimated fracture toughness are then compared with fracture/rupture data. In the report, it is shown that the behavior of CSED as a function of cladding oxide thickness is different for the different loading (stress) conditions. However, in general, creep tests, tensile tests, and impact loads type (fracture toughness) tests involve different stress and temperature states and

different fracture mechanisms. Show that the set of CSED data presented in the report is applicable for the range of stress and temperatures that are typical of dry cask storage. Although the potential complications are recognized in the paper, provide a detailed and complete CSED analysis relevant to zircaloy clad fuel, including confirmation and verification of analysis with data from high-burnup fuel.

3. Provide justification for the assumptions related to the assigned value for the critical plastic zone size and its influence on the ductility ratio, applicable to different materials. Although the applicability of the CSED methodology has been successfully demonstrated for aluminum, a similar demonstration of the applicability of this method for ferritic steels could not be reproduced. The report is not clear as to what strain should be used in the integration of stress strain behavior, namely, strain based on elongation of gauge length, strain based on reduction in cross sectional area, or an average of the two. Assuming that this plastic zone size (which is apparently considered a constant in the report) varies in the same manner as strength for different materials, provide supporting information on the variation of this plastic zone size for different zirconium-based materials under typical high-burnup conditions as a function of dry storage operating conditions.

4. In paragraph four on page 2-2 of the report, it is not clear how the assumption that J_{Ic} is the same for all fracture orientations is supportable. As an alternative to justifying this assumption, determine whether a prediction can be made regarding the most unfavorable orientation of applied stress-hydride orientation, and crack orientation with respect to the lowest fracture toughness value. This would then provide a conservative base value of fracture toughness for Zircaloy cladding.

5. In paragraph three on page 5-2, it is unclear how the second postulate is “suggested,” based on the parameters ρ_y and r which play the same physical role in characterizing the level of ductility of the material. It is also unclear how that postulate led to deriving Equation (11). Clarify the derivation and parameters in Equation 12.

6. Clarify the meaning of the symbol “σ” In Equations (6) and (8). In the context of the prior discussion of Equation (6), σ is the stress which is a function of the distance from the crack tip, whereas in Equation (8) σ evidently has constant value. Further, justify the insertion of the expression “$\sigma^2/(2E)$“ in Equation (8) which appears to be incorrect.

7. Correct the sentence as it appears prior to Equation (10). It appears that this sentence should read, “... substituting Eq. (9) in Eq. (7)....”

8. In the last paragraph on page 5-2, for a typical high burnup cladding material, a value of 40 µm has been calculated using a K_{Ic} estimate of 20 MPa√m and a yield strength of 700 MPa. However, using Equation (7) in the paper, one can obtain a value of approximately 130 µm. Justify whether a value other than $(1/\sqrt{2\pi})$ has been used for the shape factor (Y) in the fracture mechanics equation.

9. In the last paragraph of page 6-2, an internal gas pressure of 7.5 MPa has been assumed under reactor operating conditions. From this stress, a stress intensity factor of 2 MPa√m is calculated for a crack that extends through 40% of the cladding

thickness. The value of 2 MPa√m is below the threshold stress intensity factor of 5-6 MPa√m, which is required for Stage I of the delayed hydride cracking (DHC) process. However, the EPRI creep report indicates that the cladding hoop stress, under spent fuel dry storage conditions, is less than 150 MPa. Since the stress intensity factor is proportional to stress, it is not clear that the stress intensity factor, under the assumed crack size and geometry would stay within the threshold stress intensity factor for DHC. Clarify the justifications for this conclusion.

10. In paragraph four on page 3-1, clarify the meaning of the following sentence, "Despite the differences in the microstructure from the first material set, the fracture toughness values are similar for a similar range of conditions." A contradiction to this statement exists on page 4-1, paragraph 1, which says that values may be different for beta-quenched material. Additionally, page A-2 containing the tabulated data also reiterates that the "microstructure is not typical of modern cladding materials." This statement implies that the microstructure of the material used to obtain the data imparts some difference on the data. Further, justify why cladding microstructural characteristics (e.g., precipitate type, form, and morphology, annealing parameter, or texture) do not influence the fracture toughness parameters.

11. In the last paragraph on page 5-2, the value of the parameter, ρ_y, is described as being "of the order of 10 microns." However, on page 5-1, ρ_y is described as a position corresponding to σ_y. Clarify the meaning and significance of this parameter ρ_y.

12. In the first paragraph on page 6-1, the report makes reference to a paper which describes the delayed hydride cracking mechanism in CANDU pressure tubes. Please provide a copy of the relevant sections of Reference 19, *Proceeding of an International Symposium on Absorbed Specific Energy and/or Strain Energy Density Criterion,* Sept. 17-19, 1980, G.C. Sih, E. Czoboly, F. Gillemont, Editors, Martinus Nijhoff Publishers, The Hague/Boston/London.

13. On page 4-1, a K_{Ic} value of 12 MPa√m is identified as a suggested value for material with hydrogen concentrations greater than 1000 ppm independent of temperature. Provide further justification for this conclusion considering the following comment. In the abstract, the report states that one of the objectives is to address applicable regulations and regulatory guidance for the storage of spent fuel. As such, one of the concerns is the issue of retrieveability of the fuel after storage for further processing, transportation, and disposition of the spent fuel. Please evaluate the implications of the sensitivity and uncertainty in such fracture toughness analysis with respect to potential retrievability issues.

C. <u>NEI Slides from the April 18th NEI/NRC Meeting</u>

1. The FALCON code was used to predict the creep behavior of zircaloy cladding (slide 11). In those slides, good prediction was indicated for creep to rupture for only two creep specimens that appear to be from unirradiated cladding. Provide additional justification of the ability of the FALCON code to predict the creep behavior of a wide range of cladding materials and condition.

2. Provide the models and assumptions used in the development of the FALCON code, and describe how these models and assumptions are applicable to analyzing creep behavior of high burnup fuel under dry storage conditions. The models should be described in sufficient detail (with coefficients) to enable the NRC to replicate predictions of creep and creep to rupture.

References

Einziger, R.E. and R. Kohli. 1984. "Low-Temperature Rupture Behavior of Zircaloy-Clad Pressurized Water Reactor Spent Fuel Rods under Dry Storage Conditions," *Nucl. Tech.*, V. 67, American Nuclear Society, LaGrange Park, Illinois, pp. 107-122.

Ells, C. E. 1968. “Hydride Precipitates in Zirconium Alloys - A Review,” Journal of Nuclear Materials, V. 28, pp. 120-151.

Hindle, E. D. And G. F. Slattery. 1971. “Stress Orientation of Hydride Platelets in Zirconium Alloy Tubing and its Effect on Mechanical Properties,” Proceedings of the International Conference on Corrosion, British Nuclear Energy Society.

Louthan, M. R. and R. P. Marshall. 1963. Control of Hydride Orientation in Zircaloy, Journal of Nuclear Materials, V. 9, No. 2, pp. 170-184.

Proceeding of an International Symposium on Absorbed Specific Energy and/or Strain Energy Density Criterion, Sept. 17-19, 1980, G.C. Sih, E. Czoboly, F. Gillemont, Editors, Martinus Nijhoff Publishers, The Hague/Boston/London.