Partial Response to
Request for Additional Information (RAI) - Dated April 17, 2002
Regarding High Burnup Fuel in Dry Storage

B. Letter from Lynnette Hendricks (NEI) to E. William Brach (NRC), dated 10/02/01, transmitting report entitled "Creep Modeling and Analysis Methodology for Spent Fuel in Dry Storage"

Question B.1-Part 1: The statements in the last paragraph in page 23 are unclear. There seems to be confusion about the role of plastic deformation during creep and the role of the onset of plastic flow in a tensile test, which would occur at relatively higher stresses than those encountered during creep of zircaloy under dry storage. The staff is not sure how the suggested test would provide data to predict the capacity of the cladding to withstand subsequent loading challenges, perhaps during the retrieval or under accident conditions.

The paragraph cited above is restated here for easy reference: *A relevant question, from a risk assessment perspective, is how to quantify the damage, or conversely the residual capacity, of the cladding after undergoing a certain amount of creep, in order to determine the cladding capability to withstand subsequent loading challenges. The appropriate way to determine the cladding residual capacity is to conduct tensile tests for creep specimens that had undergone prior creep deformations under stresses in the elastic range, but terminated before reaching the plastic regime. The stress-strain data from such tests can then be treated in the usual way in deriving a mechanical failure criterion, using the Critical Strain Energy Density (CSED) approach or similar measures.*

Response: The proposed test is intended to be a validation test for the concept that the very low-rate creep strain and the high-rate plastic-flow strain are not additive in judging the material's capacity to resist failure. Such a test would be the simplest way to verify the effect of prior creep deformations under elastic stresses on the material's ductility as would normally be determined from a standard tensile test. This would further explain why a creep-based strain limit is not a valid measure of cladding structural capability under high-rate loading. It is argued in the report that creep rupture is a condition of plastic-flow instability at the material's ultimate tensile strength. This means that, to induce failure under creep, the stress must rise above the elastic limit to cause creep deformations to transition to the tertiary regime and high-rate plastic flow. The way in which prior creep strain can affect the cladding's load-carrying capacity is through the effect of thickness reduction. However, creep strain accumulated under "elastic stress" typical of dry storage would not introduce sufficient wall thinning, or internal material damage, to be of concern. From the authors' perspective, the proposed test would show this to be the case.

Question B.1-Part 2: We believe that the residual tensile strength at the end of storage life alone will not provide sufficient information on the retrievability of potentially "brittle" material. Accordingly, provide a summary of the mechanical properties for high burnup fuel cladding (e.g., irradiated Zircaloy-2, Zircaloy-4, Zirlo, M5, etc.) including, as a minimum, yield strength, tensile strength, elongation (total and uniform), hardness, and some form of (pseudo) usable fracture toughness.

Such information should be used in an analysis of the loading conditions expected under accident conditions (see Questions 4 and 5 below).

Response: As was discussed in the meeting of July 10, 2002, the response to this question will be provided in conjunction with the response to Questions B4 and B6, where the requested data will actually be used. It should also be noted that the scope of the response, and purpose of responding, to Questions B4 and B6 has not yet been finalized (Open item from July 10 meeting).

Question B.2: On page 29, it has been stated that a 40°C temperature rise during vacuum drying has been superimposed on all cases covered in Table 6. Clarify how the rate of change of temperature with time, $\Delta T/\Delta t$, during ramp up and ramp down was treated for creep calculations. Discuss the fractional contribution of the creep during this drying stage to the overall creep during dry storage.

Response: To illustrate the effect of the vacuum-drying cycle, we have selected Case-34 from the referenced table and carried out two creep analyses, with and without the drying cycle, for the cladding geometry shown in Figure 1. This figure depicts the cladding geometry used in EPRI-1003135, and is a simulation of the presence of a zero-strength hydride lens. The vacuum-drying cycle, which consisted of 8 hours ramp up from the initial temperature of 400°C, 8 hours hold at 440°C, and 8 hours ramp down to 400°C, was treated in the creep analysis as the initial part of the temperature history. The new calculations are depicted in Figure 2. This figure shows the hoop strain (elastic + creep) for Point A in Figure 1, for the first 24 hours of the history, which covers the vacuum drying cycle. Figure 3 shows the hoop stress history for the same time period. It should be noted, that the analysis was conducted for much longer period to see if there is a long-term decaying, or amplification, effect of the drying cycle, but the results, as expected, showed no such effect beyond 24 hours. Therefore, the results were plotted for the first 24 hours for better visualization.

As can be seen from Figure 2, the drying cycle causes an increase of less than 0.2% in the hoop strain, which is contributed by the faster creep rate due to both the temperature increase and the temperature-induced change in the pressure. The continuous rise in temperature and pressure during the first eight hours of the drying cycle induced the positive curvature that can be seen in the strain plot, showing an apparent acceleration of the creep rate similar to the tertiary regime. This is not a tertiary creep behavior, however, because the change in the creep rate is due to the change in the temperature and the applied stress, unlike classical tertiary creep, which evolves in response to wall thinning. The stress time histories are shown in Figure 3, which shows the effect of the temperature rise on the pressure for the vacuum-drying case.

Question B.3: Please elaborate on the technical meaning and significance of peak strain, mentioned in Table 7, and its relevance for dry storage.

Response: The peak strain is the membrane (mid-wall) strain calculated at Point A in Figure 1, which simulates the presence of a zero-strength hydride lens. This point is the highest stress point in the cladding cross section, and consequently shows the highest strain. It has no special relevance to dry storage other than the fact it is the highest strain value in the cladding, and consequently shows the highest cumulative damage. It should be noted, however, that if such a condition exists in storage, this "peak strain" evolves asymptotically with time and remains bounded, as shown in EPRI-1003135. In other words, the fact that the "peak strain" reflects a point of stress and strain concentration, it introduces no unusual change in the behavior of the cladding.

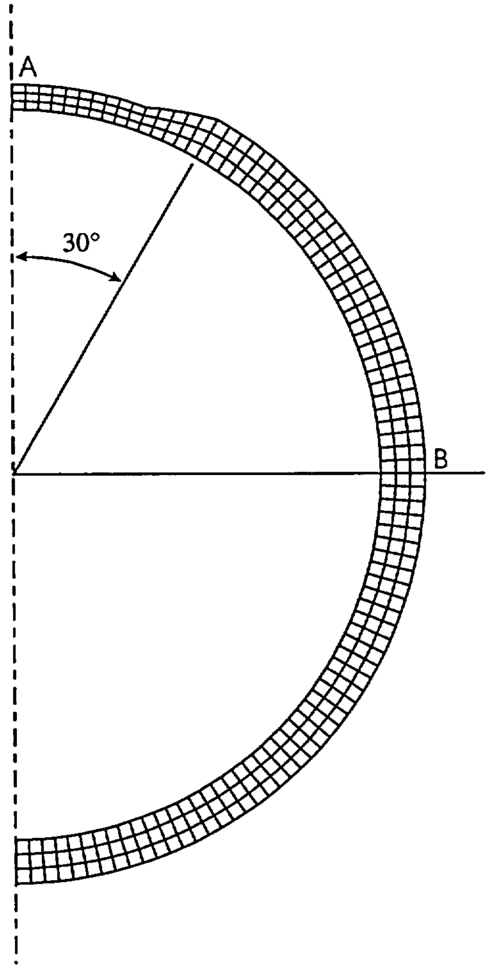

Figure 1 – FALCON R-θ Grid for Local Effect Creep Analysis of Cladding with Zero-Strength Hydride Lens

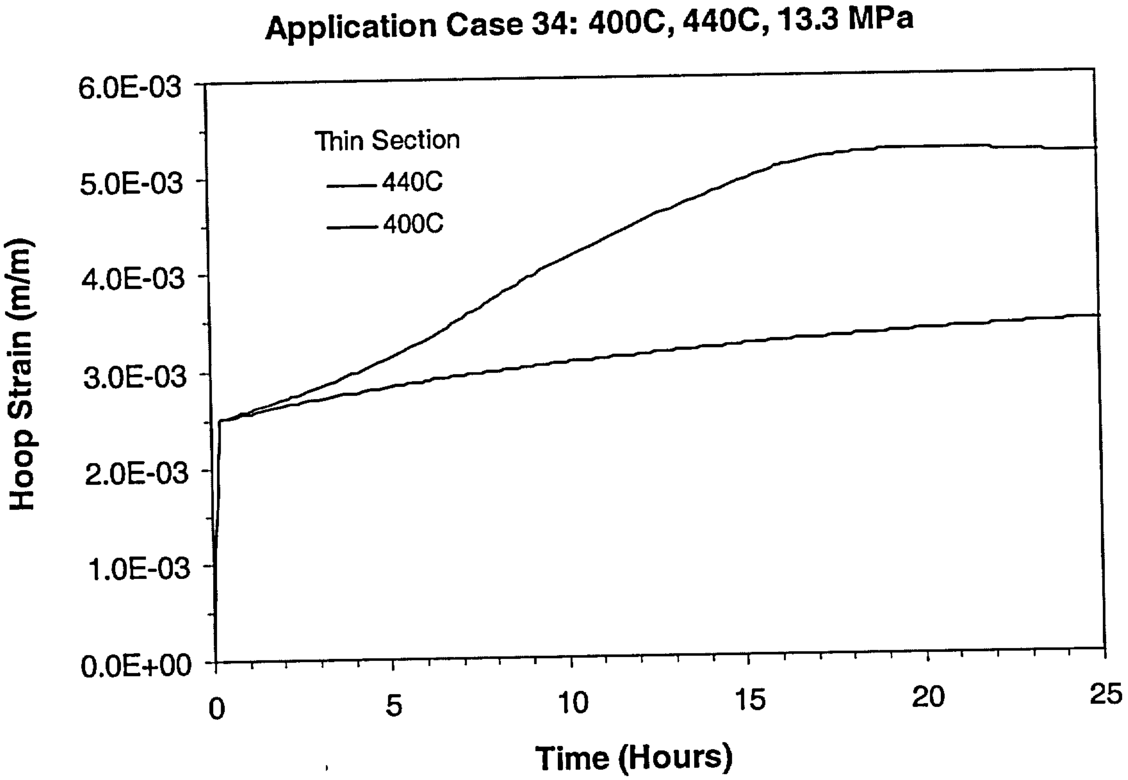

Figure 2 – Hoop Strain During Vacuum Drying Compared to the Constant-Temperature Case

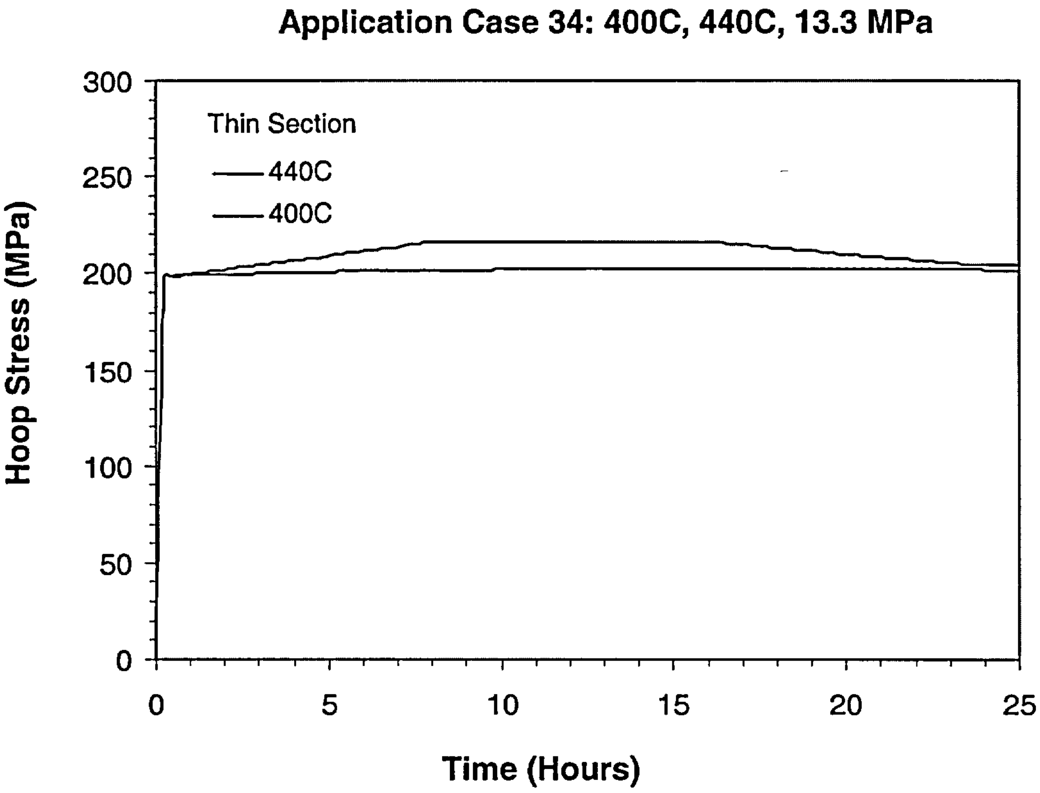

Figure 3 –Hoop Stress During Vacuum Drying
Compared to the Constant-Temperature Case