Statistical Analysis of Hydride Reorientation Properties in Irradiated Zircaloy-2

ABSTRACT: The orientation of hydrides in fuel cladding determines the anisotropic fracture behavior of Zircaloy and the failure modes of cladding tubes. Approach coupling experiments using the cladding tube deformation test and finite element analysis have successfully led to the quantification of the stress influencing reorientation of hydrides in unirradiated samples. An improved version of this procedure was applied to six samples of irradiated Zircaloy-2 from two different rods with three classes of thermo-mechanical loading. It was found that at medium maximum temperature, when no more than half of the hydrides were dissolved, the mechanical loading showed no measurable effect. When most of the hydrides were dissolved, the orientation and location of the hydrides depended strongly on the mechanical loading: The hydrides spatial location followed the hoop tensile stress. When the number of loading cycles was raised, the fraction of radial hydrides increased even for very low hoop tensile stress. The inner side of the cladding showed a marked depletion of hydrides whatever the size of the hoop stress. Since our test setup involved a tri-axial stress state, the possible influence of the other components of the stress tensor was evaluated. Through the use of a classical nucleation law, it was shown that for our test setup, the hoop stress was the important mechanical quantity. Therefore, the inner side depletion of hydrides may be attributed to three other factors: Residual stress, a memory effect, and a pumping effect by the inner liner.

KEYWORDS: Zircaloy-2, hydrides, reorientation, irradiated, fuel cladding

Introduction

The orientation of hydride platelets is a critical parameter determining the failure behavior and toughness of Zircaloy cladding tubes [1]. In a tube, when the normal to the hydride platelet is parallel to the radial direction, the hydrides are called “circumferential hydrides,” whereas when the normal to the hydride platelets is parallel to the circumferential direction, the hydrides are called “radial hydrides.” The latter hydrides promote embrittlement. Early work on this subject has provided guidelines for the fabrication of cladding tubes that favors the orientation of hydrides toward the circumferential direction [2,3].

These studies have been extended to determine the thermo-mechanical conditions of reorientation of hydrides from the circumferential to radial orientations. According to kinetic models, this reorientation is characterized by two threshold stresses oriented with respect to the orientation of hydrides platelets under a stress free state. The lower threshold stress is related to the minimal tensile stress perpendicular to the normal of the hydrides in their natural orientation leading to the first appearance of reoriented hydrides. The upper threshold stress corresponds to the minimal stress necessary to reorient all possible hydrides.

The commonly used procedure to determine the reorientation stress for a particular material is to machine a tapered uni-axial tension specimen [4–7]. With such a specimen, the tensile stress can be varied continuously in the range where reorientation takes place. The determination of a lower and an upper threshold stress is straightforward. In such a study, the specimens can be hydrogenated prior to the application of a reorientation thermo-mechanical loading using a maximum temperature sufficient to dissolve all the hydrides. The latter also minimizes any memory effect due to a possible preference of precipitation at a previously occupied site.

Whereas general agreement on test techniques for plate materials has been reached, standard testing

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for hydride reorientation in tubes is still being discussed. One approach is to prepare a flat sample from the tube [8]. This technique may not preserve the texture of the alloy and produces residual stresses that can affect the results of the reorientation test. The tube can be internally pressurized during the hydrogenation procedure [9]. The main advantage of this approach is the constant hoop stress within the test sample that facilitates the post-test analysis. A third technique, which does not require the development of a specific test device is to use a ring tensile test setup [10,11]. This experimental approach has to be complemented by a finite element analysis (FEA) to determine the stress field. Since handling irradiated materials is difficult, the last method has been chosen using the test setup depicted in Fig. 1. This method of testing enables us to compare results obtained from reorientation tests with fracture tests on cladding material [12].

Among the parameters that have been studied as possibly influencing hydride reorientation are the maximum temperature, the hydrogen concentration, the number of loading cycles, the orientation with respect to rolling direction, and the initial thermal treatment. A recent study on irradiated BWR cladding tubes [13] showed that for tubes with a burn-up of about 50 GWD/TU and for a dissolution temperature of around 300°C, the lower stress threshold for hydride reorientation was less than 70 MPa.

The reorientation threshold is defined for tests using a peak temperature above the terminal solid solubility for dissolution: All of the hydrogen contained in the sample can form reoriented hydrides on cooling if the reorientation stress is large enough.

During multiple loadings, hydrides that have not been reoriented during the previous loading step, may dissolve, and can be reoriented during the current loading step [9]. For samples recovered from a nuclear power plant, the density of hydrides is higher on the external side than the central and inner regions of the cladding tube. Thus, temperature cycling may have an important effect on the reorientation behavior by redistributing the hydrogen within the tube cross-section.

In this document, we describe the characteristics of the cladding tube, the hydride reorientation tests, and the analysis procedure. The analysis provides spatial distributions of hydrides as well as a quantification of the geometric characteristics of the hydrides over the whole tube cross-section. The picture analysis is then coupled with an FEA of the test setup to determine the stress that each hydride encountered and thus give information on the local stress leading to reorientation. A model based on a precipitate nucleation law is used to determine the component of the stress tensor leading to reorientation; the effect of the tri-axial stress state is shown to have no influence on the reorientation of hydrides.

### Test Description

**Sample Characteristics**

This study was done on six Zircaloy-2 (LK3/L) test samples (Table 1) removed from a Swiss BWR. The manufacture process included annealing with an accumulated annealing parameter of $6.31 \times 10^{-15}$ h. The
samples were taken from two rods that had undergone seven reactor cycles for a burn-up of around 66 GWd/TU. These samples have been thoroughly examined after irradiation and fully characterized [14].

The hydrogen concentration was measured by hot gas extraction on samples extracted from the same rods. The measurements presented in Table 1 are the hydrogen concentrations in segments contiguous with the tested samples. The hydrogen concentration was expected to exhibit no significant variations between contiguous segments. The measurement technique enabled separation between hydrogen in the metal matrix and in the outer oxide layer. For this study, the hydrogen concentration in the metal matrix was of most interest. Figure 2 shows the chemically etched cross-section of the cladding tube when received from the power plant. In this state, the measured fraction of radial hydrides was around 10 % for rod AEB071-E4 and 9.2 % for rod AEB067-E4.

**Loading and Testing Characteristics**

To study hydride reorientation, the approach was as follows: A test sample, 12 mm long, was extracted from the defueled and cleaned fuel rod. Then, it was submitted to a thermo-mechanical loading to promote hydride reorientation (Fig. 3). The cooling rate was sufficiently slow to reach equilibrium [10]. After chemical etching, a micrographic analysis of the cross-section of the sample was done. The reorientation stress was determined using an FEA of the test setup.

Taking into account the structural and loading symmetries, only one eighth of the test setup was modeled. According to previous work [10] and since the contact surfaces were lubricated, the friction

![FIG. 2—Cross-section macrographs of the rods before reorientation tests.](image1)

![FIG. 3—History of the thermo-mechanical loading during one cycle.](image2)

<table>
<thead>
<tr>
<th>Segment</th>
<th>$H_{\text{Total}}$ (ppm)</th>
<th>$H_{\text{Metal Concentration}}$ (ppm)</th>
<th>$T_{\text{max}}$ (°C)</th>
<th>$F_{\text{hold}}$ (N)</th>
<th>Loading Cycles</th>
<th>Burn-up (MWd/kgU)</th>
<th>Calc. Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEB067-E4-GC</td>
<td>251.</td>
<td>222.</td>
<td>394.</td>
<td>283.</td>
<td>1</td>
<td>66.0</td>
<td>14</td>
</tr>
<tr>
<td>AEB067-E4-HI</td>
<td>241.</td>
<td>215.</td>
<td>395.</td>
<td>283.</td>
<td>3</td>
<td>61.0</td>
<td>18</td>
</tr>
<tr>
<td>AEB067-E4-HD</td>
<td>297.</td>
<td>271.</td>
<td>334.</td>
<td>284.</td>
<td>1</td>
<td>63.6</td>
<td>16</td>
</tr>
<tr>
<td>AEB071-E4-FF</td>
<td>325.</td>
<td>296.</td>
<td>422.</td>
<td>285.</td>
<td>1</td>
<td>67.4</td>
<td>11</td>
</tr>
<tr>
<td>AEB071-E4-FK</td>
<td>355.</td>
<td>318.</td>
<td>422.</td>
<td>283.</td>
<td>3</td>
<td>66.8</td>
<td>13</td>
</tr>
<tr>
<td>AEB071-E4-IC</td>
<td>285.</td>
<td>258.</td>
<td>355.</td>
<td>283.</td>
<td>1</td>
<td>63.1</td>
<td>17</td>
</tr>
</tbody>
</table>

*Segment designation is as follows: Fuel assembly–rod–sample.*
coefficient at the contact interface between the mandrel and the sample was set to zero. The material behavior was taken to be elasto-plastic for the mandrel and the cladding tube material. As checked with the computations, the size of the thermo-mechanical loading was not big enough to reach the yield strength of the cladding.

The main characteristics of the thermo-mechanical loading are summarized in Table 1. They can be divided in three categories as follows:

- **High temperature**, 394 and 422°C, one loading cycle
- **Medium temperature**, 334 and 355°C, one loading cycle
- **High temperature**, 395 and 422°C, three loading cycles

These three types of loading permit coverage of a wide range of reorientation conditions for each rod.

**Terminal Solubility Under Testing Conditions**

Figure 4 depicts the dissolution terminal solid solubility (TSSD) of hydrogen for irradiated and unirradiated Zircaloy-2. The determination of the stress leading to the reorientation of hydrides implies a reliable observation of the location, size, and orientation characteristics of each hydride revealed by the chemical etching process. To
get information on the whole cross-section of the cladding tube, a software for automatic segmentation was developed using the C++ language. Hydrides were considered circumferential when they were oriented within \(+/-45^\circ\) from the circumferential direction. Calculations have shown that most of the initial hydrides were oriented in a range of \(+/-15^\circ\) with respect to the circumferential orientation. The minimal length considered for hydrides was 15 \(\mu\)m. The algorithm used in this software was as follows:

- Stitch together macrographs to obtain a picture of the whole tube cross-section
- Convert pictures in gray level using the picture red channel
- Convert gray level into black and white using a cluster threshold algorithm
- Identify circumferential hydrides (Fig. 5):
  - Mark connected black pixels in the circumferential direction
  - Make range selection on the marked pixels
  - Determine size and orientation characteristics, and filter out particles that do not satisfy selection criteria
  - Erase circumferential hydrides from the original picture
- Identify radial hydrides (Fig. 6):
  - Mark connected black pixels in the radial direction
  - Make range selection on the marked pixels
  - Determine size and orientation characteristics, and filter out particles that do not satisfy selection criteria

This software enabled sampling information on the whole cross-section of the cladding tube. The collected data were hydride orientation, location, and size. Since the analysis was done on the whole cross-section, the orientation with respect to the cladding tube was defined in cylindrical coordinates based on the center of the cladding tube. The coordinates of the applied mechanical loading are depicted in Fig. 7. The treatment of the whole cladding tube permitted computation of the weighted distribution of the radial, \(d_r\), and circumferential, \(d_\theta\), length of hydrides, as defined by

![Fig. 5—Segmentation of circumferential hydrides: (a) Original picture and (b) precipitates identified as circumferential hydrides. Only the top right part of the rod is depicted.](a) AEB067-E4-GC (b) AEB067-E4-GC

![Fig. 6—Segmentation of radial hydrides: (a) Original picture and (b) precipitates identified as radial hydrides. Only the top right part of the rod is depicted.](a) AEB067-E4-GC (b) AEB067-E4-GC
\[ d_r(r) = \frac{1}{L} \frac{\partial}{\partial r} \sum_{r_j < r} l_j \quad \text{and} \quad d_{\theta}(\theta) = \frac{1}{L} \frac{\partial}{\partial \theta} \sum_{\theta_j < \theta} l_i \]

where:

\( l_i \) denotes the length of the \( i \)-th hydride located at position \((r_i, \theta_i)\).

The derivatives were calculated numerically; data were filtered in order to remove high frequency variations. To enable comparison, these distributions were normalized by the sum of hydrides length, \( L \).

**Global Quantities**

The etching conditions can vary from one sample to another (Fig. 8), thus modifying the apparent size of hydrides. To minimize this variation, only the lengths of the hydrides were measured because this dimension is not much affected by a variation of the etching conditions. Once the identification of the hydrides on the whole cross-section was done, the averaged quantities of each type of hydride were computed (Table 2 and Fig. 9).

During the segmentation and analysis process, the inner, heavily hydrided liner and outer oxidized layer were automatically removed, as they were not relevant for our study. Consequently, the total length of hydrides and the total hydrogen concentration were not correlated.

For the high temperature loadings for one or three cycles, the fraction of reoriented hydrides and the most frequent hydride length were similar for each rod. More hydrides were reoriented when the number of cycles was increased: About 20% with one cycle tests and about 30% with tests using three cycles. This fraction was not affected by the initial difference in hydrogen concentration of the two rods, unlike in the tests using a medium temperature. The difference between these two testing regimes was the quantity of remaining hydrides at the maximum temperature. Thus, we infer that the quantity of remaining hydrides when the sample is mechanically loaded has an influence on the fraction of hydrides that are reoriented.

**Location and Spatial Distribution**

The locations of hydrides of various lengths are depicted in Fig. 10 for circumferential hydrides and in Fig. 11 for radial hydrides.

Radial hydrides were preferentially located in the outer third part of the tube when the maximum temperature was high. When the maximum temperature was medium, radial hydrides were almost homogeneously located with a slightly higher presence in the middle part of the tube wall. For the same hydrogen concentration, a higher density of radial hydrides led to a lower density of circumferential hydrides. This conclusion was particularly demonstrated with three loading cycles at the high maximum temperature. The external loading had less influence when the maximum temperature was low than when it was high. When the higher testing temperature was used, the biggest hydrides only formed at the load application points on the outer part of the cladding. When the medium temperature was used, the biggest hydrides were observed in the inner part of the cladding at 90° from the load application points.
Figures 12 and 13 depict the distribution of hydrides in the radial and the circumferential directions, respectively. For samples that had a high maximum temperature, there were two peaks in the number of radial hydrides at the load application points. These two peaks for the radial hydrides corresponded to two minima for the circumferential hydrides. This quantification confirmed the visual impression in Figs. 10 and 11. This localization of reoriented hydrides was not reflected by the overall measure of fraction of reoriented hydride. It is thus important when assessing the toughness of a tube with respect to radial hydrides to ensure that the loading has been homogeneous and not localized, as in the present study.

With the medium peak temperatures, the influence of the externally applied load was expected to be less important due to the lower quantity of dissolved hydrogen. This expectation was verified for sample AEB067-E4-HD where the reorientation fraction was around 16%. This expectation was not fulfilled by sample AEB071-E4-IC, which was tested under similar conditions, but where the reorientation fraction was about 31%. As indicated in Fig. 4, the amount of dissolved hydrogen was slightly greater in the latter than the former specimen, although it is unlikely that such a small difference in hydrogen in solution would lead to a difference of a factor of two in the reorientation fraction. This behavior could be explained by a high hydrogen concentration in the liner of this specimen. If true, the hydrogen concentration in the bulk of the cladding tube would be lower than estimated, providing favorable conditions for hydrides reorientation. Thus, it is difficult to draw a conclusion on the effect of the thermo-mechanical loading when much of the hydrogen is not in solution at the maximum temperature. The reproducibility between these two samples was poor despite the testing conditions being close, and no further analysis in terms of applied stress is presented.

<table>
<thead>
<tr>
<th>Loading</th>
<th>AEB067-E4-GC</th>
<th>AEB067-E4-HI</th>
<th>AEB071-E4-FF</th>
<th>AEB071-E4-FK</th>
<th>AEB071-E4-IC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen content (ppm)</td>
<td>222.</td>
<td>215.</td>
<td>271.</td>
<td>296.</td>
<td>318.</td>
</tr>
<tr>
<td>Total length (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circumferential</td>
<td>44.</td>
<td>66.</td>
<td>152.</td>
<td>90.</td>
<td>67.</td>
</tr>
<tr>
<td>Radial</td>
<td>29.</td>
<td>28.</td>
<td>24.</td>
<td>27.</td>
<td>36.</td>
</tr>
<tr>
<td>Sum</td>
<td>55.</td>
<td>95.</td>
<td>180.</td>
<td>114.</td>
<td>93.</td>
</tr>
<tr>
<td>Most frequent length (μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total quantity</td>
<td>1237</td>
<td>1493</td>
<td>2354</td>
<td>1414</td>
<td>1057</td>
</tr>
<tr>
<td>Fraction of radial (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total length</td>
<td>19.3</td>
<td>30.8</td>
<td>15.8</td>
<td>21.3</td>
<td>28.5</td>
</tr>
<tr>
<td>Total quantity</td>
<td>21.9</td>
<td>35.0</td>
<td>29.3</td>
<td>34.0</td>
<td>40.7</td>
</tr>
</tbody>
</table>

FIG. 8—Effect of etching on the apparent size of the hydrides.

Table 2—Averaged quantities on the cladding tube cross-section.

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We are interested in the loading conditions leading to the formation of radially oriented hydrides because of their importance when assessing the integrity of cladding tubes. The formation of radially oriented hydrides is expected to be driven by the tensile stress in the circumferential direction, i.e., hoop stress. Figure 14 depicts the hoop stress calculated by FEA for one cycle and three cycle loadings at high maximum temperatures.

Figure 15 displays the fraction of radial hydrides as a function of the hoop stress for the two temperature histories. For the single cycle loading at high maximum temperature, the fraction of reoriented hydrides exhibited a lower threshold just below 50 MPa for rod AEB067-E4. For rod AEB071-E4, the determination of the lower threshold for reorientation was not clear but was assessed to be around 50 MPa.

With multiple loading, the reorientation curves for both specimens showed a plateau once the hoop stress was positive. In previous work using uniaxial loading on unirradiated material, multiple cycles increased the maximal fraction of reoriented hydrides without affecting the lower and upper reorientation thresholds [5]. The behavior observed here was a constant fraction of radial hydrides in any part submitted

![Graph showing stress distribution and reorientation behavior](image)

**FIG. 9**—Fraction of radial hydrides before and after reorientation tests based on total length.

**Stress Distribution**

**Reorientation Behavior**

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![Graph showing stress distribution and reorientation behavior](image)

**FIG. 10**—Location of circumferential hydrides. Length classes vary from specimen to specimen.
to a tensile hoop stress. When the spatial distribution of hydrides was compared with the areas where the lower threshold stress was exceeded (Fig. 16), it is seen that the inner side of the cladding tube exhibits atypical behavior; few hydrides precipitate, so even if the hoop tensile stress was large enough, there was no hydride reorientation. The concentration of hydrogen was low in this area.

A definitive conclusion on the effect of applied stress on hydride reorientation cannot be drawn without knowing the residual stress state in the sample. Although fuel performance codes provide the history dependence of the residual stress state of a rod, this stress estimate is for a complete rod and cannot be applied directly to an extracted and defueled segment. From a previous study [8], the residual hoop stress is expected to be compressive on the inner side and tensile on the outer side of the tube. Under such a residual stress state, the threshold applied stress determined above may be lower than one determined

FIG. 11—Location of radial hydrides. Length classes vary from specimen to specimen.

FIG. 12—Distribution of hydrides, averaged in the circumferential direction.
FIG. 13—Distribution of hydrides, averaged in the radial direction.

FIG. 14—Distribution of the hoop stress for (a) one cycle loading at the high maximum temperature and (b) three cycle loading at the high maximum temperature. Tensile direction is along the y-axis.

FIG. 15—Fraction of radial hydrides as a function of the hoop stress.
with no residual stress. When three cycles were imposed, the coincidence that the reorientation threshold corresponded to the switch between compressive and tensile residual hoop stress seems unlikely. Either the residual stress was very low compared with the applied stress, or the residual stress annealed out when the samples were heated.

The reorientation of hydrides was absent at high tensile stress on the inner side of the cladding because of the low concentration of hydrogen, i.e., few hydrides. Three possible mechanisms are responsible for this observation.

- The outer side of the tube is cooler than the inner side during reactor operation and wet storage. Hydrogen diffuses down the temperature gradient through the tube wall favoring hydrides precipitation in the outer region.
- Preferential precipitation of hydrides on previously occupied sites [6]—the “memory effect”—prevents precipitation at other sites even with a homogeneous temperature distribution.
- The inner liner on the test material is a preferred site for hydride precipitation because it has a lower terminal solid solubility than the material of the remainder of the tube wall. Consequently, hydrogen is drained from adjacent areas—the “pumping effect”—leading to depletion in hydride precipitates in the inner regions.

**Interaction Energy for Reorientation**

The effect of stress tri-axiality on the formation of reoriented hydrides has not been assessed because most studies on hydride reorientation have been done in uni-axial tension. The reorientation of hydrides was observed with very low hoop stresses with multiple cycles loading. A tri-axial stress may play a role in this behavior by favoring reorientation where the hoop stress is not necessarily the largest component of the stress and other components may be involved. The current test setup induced a multi-axial stress state; the hoop and axial stresses dominated but varied continuously within the sample, whereas the radial and shear components of the stress tensor were so small that they could be ignored.

To assess the consequences of such a stress state, we have to determine the mechanical quantity that determines the reorientation. A widely used model for reorientation [7,19–22] assumes that the fraction of reoriented hydrides is driven by the nucleation rate in two preferential directions, the radial and circumferential directions. The quantity of importance is the difference between the interaction energies for radial and circumferential hydrides, $\Delta E_{int}^{R-C}$, defined by

![FIG. 16—Areas where orientation should occur according to threshold stress and depending on the loading type.](image-url)
\[ \Delta E_{\text{int}}^{R-C} = \alpha E_{\text{int}}^R - \beta E_{\text{int}}^C \]

where:
\( \alpha, \beta \) = two constants depending on the inter- and intra-granular nucleation volume and
\( E_{\text{int}}^R, E_{\text{int}}^C \) = interaction energies for radial and circumferential hydride formation, respectively.

With this approach and data proposed by Ref 7, the energy driving the process is given by

\[ \Delta E_{\text{int}}^{R-C} = \frac{1}{2} V_{\text{intra}}^0 E_{\text{int}}^C + ((1 - \xi^0) V_{\text{inter}}^0 + \xi^0 V_{\text{intra}}^0) E_{\text{int}}^R \]

where:
\( V_{\text{intra}}^0 = 4.3 \times 10^{-27} \) \( \text{m}^3 \) and \( V_{\text{inter}}^0 = 15 \times 10^{-27} \) \( \text{m}^3 \) = critical nucleus volumes for intra- and inter-granular hydrides, respectively, and
\( \xi^0 \) = fraction of intra-granular radial hydrides, taken as 0.3.

The interaction energy for hydrides in the radial and circumferential directions is the doubly contracted tensor product between the transformation strain and the stress due to externally applied load. Their values are

\[ E_{\text{int}}^C = 0.072 \sigma_{rr} + 0.0456 \sigma_{\theta \theta} + 0.0456 \sigma_{zz}, \quad E_{\text{int}}^R = 0.0456 \sigma_{rr} + 0.072 \sigma_{\theta \theta} + 0.0456 \sigma_{zz} \]

The dependence of the fraction of radial hydrides with respect to the interaction energy is depicted in Fig. 17. This dependence is similar to that of the hoop stress, Fig. 15, especially for the tests using three loading cycles, confirming that hydrides reorient as soon as the interaction energy is positive. The reorientation at low hoop stress for tests using multiple cycles cannot be attributed to the non-hoop components of the stress tensor.

**Conclusion**

In this work, we have analyzed the thermo-mechanical conditions leading to the formation of radially oriented hydrides in irradiated Zircaloy-2 cladding tubes. Three different loading sequences were used on two different rods. The test setup provided multi-axial thermo-mechanical loading. Only two of our loading scenarios were amenable to analysis. In the tests using a medium maximum temperature, many hydrides were not dissolved, and only a small fraction of hydrides was susceptible to reorientation. In these tests, the external applied stress had no significant influence on the final distribution and presence of radially oriented hydrides.

For tests using a high maximum temperature, most of the hydrogen was in solid solution, and the mechanical loading had a strong influence on the hydride location and orientation in both rods. The overall fraction of reoriented hydrides was similar, independent of the initial hydrogen concentration, confirming that at the maximum test temperature, almost all hydrides were dissolved.

The effect of increasing the loading cycles was to increase the fraction of radially oriented hydrides. This result was expected from the literature review: Hydrides that have not been reoriented at one loading cycle may be reoriented with subsequent cycles. The cycling tended to homogenize the distribution of hydrides in the radial direction.

The hoop stress determined the threshold of reorientation. For one cycle at the high temperature, reorientation started at a hoop stress of about 50 MPa. This value was lower than the one determined in our
previous study on unirradiated Zircaloy-2, which was in the range 65–74 MPa. This reduction was consistent with observations of reorientation of hydrides in irradiated Zircaloy-2 tubes [13]. When three cycles were used with a high maximum temperature, hydrides reoriented once the hoop stress was positive. This last result was not expected from previous studies on unirradiated test samples.

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References


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