Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

SRNL
SAVANNAH RIVER NATIONAL LABORATORY

SRNL-STI-2014-00589

Comparison of Ring Compression Testing to Three Point Bend Testing for Unirradiated Zirlo Cladding

P.S. Korinko, R. L. Sindelar, R. L. Kesterson

Keywords: Hydrides, Hydrogen, Mechanical Testing, Ductile-Brittle Testing

For publication in the
Proceedings of the ASME 2015 Pressure Vessel and Piping Conference, PVP15
July 19-23, 2015, Boston, Massachusetts, USA

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy.

Proceedings of the ASME 2015 Pressure Vessel and Piping Conference
PVP15
July 19-23, 2015, Boston, Massachusetts, USA

PVP2015-45984

COMPARISON OF RING COMPRESSION TESTING TO THREE POINT BEND TESTING FOR UNIRRADIATED ZIRLO CLADDING

Paul S. Korinko
Savannah River National Laboratory
Aiken, South Carolina, USA

Robert L. Sindelar
Savannah River National Laboratory
Aiken, South Carolina, USA

Ronald L. Kesterson
Savannah River National Laboratory
Aiken, South Carolina, USA

ABSTRACT

Safe shipment and storage of nuclear reactor discharged fuel requires an understanding of how the fuel may perform under the various conditions that can be encountered. One specific focus of concern is performance during a shipment drop accident. Tests at Savannah River National Laboratory (SRNL) are being performed to characterize the properties of fuel clad relative to a mechanical accident condition such as a container drop. Unirradiated ZIRLO tubing samples have been charged with a range of hydride levels to simulate actual fuel rod levels. Samples of the hydrogen charged tubes were exposed to a radial hydride growth treatment (RHGT) consisting of heating to 400°C, applying initial hoop stresses of 90 to 170 MPa with controlled cooling and producing hydride precipitates. Initial samples have been tested using both a) ring compression test (RCT) which is shown to be sensitive to radial hydride and b) three-point bend tests which are less sensitive to radial hydride effects.

Hydrides are generated in Zirconium based fuel cladding as a result of coolant (water) oxidation of the clad, hydrogen release, and a portion of the released (nascent) hydrogen absorbed into the clad and eventually exceeding the hydrogen solubility limit. The orientation of the hydrides relative to the subsequent normal and accident strains has a significant impact on the failure susceptability. In this study the impacts of stress, temperature and hydrogen levels are evaluated in reference to the propensity for hydride reorientation from the circumferential to the radial orientation. In addition the effects of radial hydrides on the Quasi Ductile Brittle Transition Temperature (DBTT) were measured. The results suggest that a) the severity of the radial hydride impact is related to the hydrogen level-peak temperature combination (for example at a peak drying temperature of 400°C; 800 PPM hydrogen has less of an impact/ less radial hydride fraction than 200 PPM hydrogen for the same thermal history) and b) for critical strains in post drying handling, storage and accident conditions the 3 point bend strain tolerance is less affected by radial hydrides than the conventional ring compression test (the radial hydride related Quasi DBTT associated with a three point bend straining is lower (better) than that measured by the ring compression tests).

NOMENCLATURE

DBTT – Ductile Brittle Transition Temperature
EDM- Electrical Discharge Machined
FEA –Finite Element Analysis
MPa – Mega Pascals
PPM – parts per million by weight
RCT – Ring Compression Test
RHGT – Radial Hydride Growth Treatment (cooling from 400°C to RT while under a preset (initial) hoop stress)
SRA – Stress Relief Anneal
TPB – Three Point Bend
ZIRLO- Zr-1%Nb-1%Sn–0.1%Fe cladding alloy
Zry-4 – Zircoloy-4 alloy Zr-1.45% Sn-0.21% Fe-.16% Cr cladding alloy

INTRODUCTION

A primary point of concern for long term spent fuel dry storage planning is that when the cladding experiences the thermal-mechanical conditions of the storage container drying process and subsequent transport that the risk for clad failure during normal and accident conditions is understood and minimized. The generation of radial reoriented hydrides in the clad during cooling with clad hoop stresses will alter some cladding properties and thus data on the factors influencing the reorientations and the subsequent property impacts is important for modeling and design.

Hydride precipitation and reorientation:

During normal fuel operation the clad reacts with the water-coolant and forms ZrO_2 and hydrogen. Some of the generated hydrogen is absorbed into the cladding thus producing the observed levels of internal hydrogen. Primarily because of the temperature differential across the clad, the hydrides strongly tend to be circumferentially oriented and near the OD surface. Since the corrosion (and temperature) varies along the fuel rod length and to a lesser extent azimuthally the absorbed hydrogen levels also vary. For example Zircaloy 4 clad PWR fuel at discharge may have hydrogen levels varying from 100 ppm at the rod bottom to over 600 ppm at the peak corrosion areas (Reference 1).

Hydrogen has a limited solubility in the zirconium matrix and when the solubility is exceeded the H precipitates as zirconium hydrides. The solubility as a function of temperature has been well characterized (for example reference 2). Figure 1 shows typical solubility curves as a function of temperature for Zry-4. As shown, there is a difference in the dissolution and solution curves that result in a delay in hydride precipitation at the start of cooling. Irradiation damage will have an impact on the hydride precipitation characteristics also.

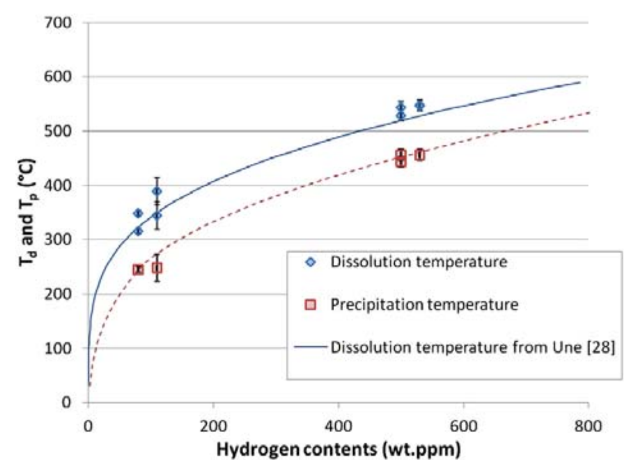


Figure 1 – An example of a Hydrogen Solubility in Zry-4 (Reference 3)

During preparation for long term storage, the fuel assemblies will be loaded from the spent fuel pool into storage containers and then will be subject to a dry out procedure to remove residual water transferred with the fuel from the storage pool. A potential dry out will include self-heating of the fuel to temperatures near 400°C. At this temperature about 200 ppm of the clad hydrogen will be in solution. As the clad cools, this H will precipitate as hydrides. The reprecipitation of hydrides depends largely on the cooling rate and hoop stress. Depending on the hydride orientation, the hydrides represent potential crack paths through the clad wall. Particularly if there is a hoop tensile stress then the formation and presence of radial hydrides are of concern.

The evaluation of hydride reorientation and DBTT effects necessitates a test matrix that includes variations in testing temperatures, reorientation stresses and an understanding of the changes in solubility levels for the various test conditions. For the series of test reported here it was assumed that a temperature of 400°C per NRC Spent Fuel Project Office, Interim Staff Guidance -11, Revision 3 as the peak temperature that the fuel would experience. At this temperature the hydrogen solubility is about 200 to 250 ppm. This implies that if a section of the cladding had 400 ppm that about 50% of the hydrogen would go into solution and be available to precipitate out as hydrides with subsequent cooling. Likewise, if the section of cladding has 200 ppm or less then effectively all of the hydrogen would go in solution and be available to form hydrides upon cooling. Due to the importance of the relative amount of radial hydrides for some testing conditions, the percentage of hydrogen in solution to that remaining as hydrides at the peak temperature is an important factor in evaluation radial hydride impacts.

Clad stress level variations:

During dry storage and without significant pellet expansion the primary clad stress is in the hoop direction and is a function of the internal gas pressure from fission gas release, initial fill gas and in some designs gas generation from rod internal burnable neutron absorbers. The majority of the internal gas is in the fuel rod plenum(s) which typically will be at lower temperatures than the peak clad temperatures. A typical peak hoop stress of 90 MPa is used for storage design (reference ISG 11 rev 3); however, higher internal pressures/hoop stresses are possible for some fuel rod conditions. If a PWR fuel rod operated with an internal pressure near the rod external coolant pressure of 15.5 MPa (2250 psi) and it is assumed that the internal gas temperature (in the plenum) during the drying anneal would be near the internal gas temperature during reactor operation then the resulting hoop stress during a 400°C drying anneal would be about 128 MPa. There is some conservatism in this since the plenum will probably be cooler than peak rod temperatures during drying. Considering these factors, values of 90 MPa and 130 MPa were chosen to study the effects of hoop stresses on hydride reorientation. Likewise in the rare case where the internal rod pressure peaks at near 19 MPa (2800 PSI) the resulting hoop stress during dry out would be near 160 MPa: thus, an extreme condition 170 MPa (for a series of 40 MPa increments) was also included in the test matrix.

Ductile to Brittle Transition Temperatures (DBTT):

For spent fuel transport, storage, and retrieval and re-transport it is of value to know the degree of strain that can be accommodated by the clad prior to reaching a point of unstable crack initiation and propagation. Classically, this characteristic is a temperature /material condition that has been associated with DBTT. However, for spent fuel clad which is embrittled by radiation damage and hydride formation and tested by RCT and bend tests it is proposed that the DBTT and measured “ductility” are relative terms and the ductile and brittle temperature regimes are very much test condition dependent.

There are basically three modes of stress present in a nominal container drop accident (reference 4); Mode I and II are bend modes (lateral deflection between grid support points) represented in this testing by TPB tests and Mode III which is a pinch or diameter crush mode represented by ring compression testing. It is proposed that in potential container drop type accidents that Mode I and II are likely to be more applicable than Mode III when considering the restricted diameter deflection with pellets in the rod and other contributing factors.

The presence of radial hydrides is known to negatively impact the DBTT as measured in ring compression tests, which is representative of Mode III conditions. However, it was not known how the Mode I and II conditions would be impacted by radial hydrides. Thus, this test series was performed to compare RCT and bend tests regarding sensitivities to radial hydrides on the cladding ability to withstand deformation in the stress/strain modes.

EXPERIMENTAL

Materials

Stress relief annealed (SRA) ZIRLO^{TM} tubing was used for this study. The nominal composition of ZIRLO is 1% Sn, 1% Nb, 0.1% Fe, and 0.1-0.14% O. The tube samples had nominal dimensions of 9.52 mm OD and 8.38 mm ID (0.375 inch OD and 0.330 inch ID). Tube sample were cut to two lengths of 8 mm for the ring test and 100 mm for the bend test. The initial hydrogen charging was performed on longer tubes (38 cm/15 inches long) from which the samples were later removed. High purity hydrogen and high purity argon, 99.95% purity, were used to charge and pressurize the ZIRLO tubes, respectively.

Specimen Preparation

Tubing samples were pre-hydrided to target levels of 100 ppm, 200 ppm, 400 ppm and 800ppm. The area designated for hydrogen charging was lightly abraded on OD surface using 600 grit silicon carbide paper and wiped with absolute alcohol. The cleaned samples were placed in a stainless steel based tube furnace and evacuated within 20 minutes of final cleaning, consistent with a process developed for Zry-4 [5]. The samples were evacuated for a minimum of 12 hours prior to the introduction of the appropriate aliquot of hydrogen.

The furnace tube was heated to 400°C at a rate of 10°C/min, held for 30 minutes, and then cooled at a rate of 5°C/min to 100°C and allowed to convectively cool to RT. Variation in hydrogen content was observed along the tube axis. The ring test samples were cut from the mid-section of the charged tubes where the hydrogen levels were most consistent. The bend test samples were also cut from the center of the charged and aged tubes. The stress- strain maximums are concentrated near the sample mid length at the position of contact with the upper roller. The measured axial hydrogen level varied more in the higher hydrogen content samples. While the hydrogen variability needs to be considered, the DBTT testing with RCT and TPB samples are sensitive to hydride orientation which is assumed to not be strongly affected by these observed variations in hydrogen within the mid tube length.

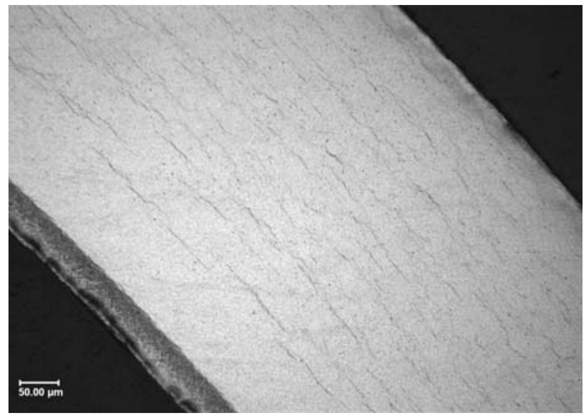


Figure 2 Example hydride structure with ID hydride rim

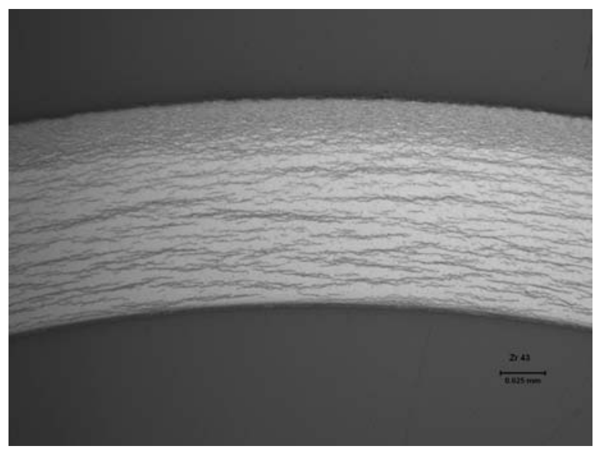


Figure 3 Example of hydride structure with OD hydride rim

The sample hydriding was observed to produce a uniform and nominally circumferential internal hydride structure, as shown in Figures 2 and 3. Depending on hydrogen charging absorption an ID or OD hydride rim was observed for samples with > 400 ppm hydrogen.

Radial Hydride Growth Treatment (RHGT)

One objective of this evaluation was to measure the effects of hoop stress on hydrogen reorientation during cooling. Pre-hydrided samples were pressurized with argon to achieve the desired stress for the RHGT; higher pressures than indicated by Boyles’ law were needed since the entire system volume was not heated. The sample was inserted into the furnace and the furnace was heated to 400°C at a rate of 10°C/min, held for one hour, and cooled at a rate of 5°C/hr to 200°C and then air cooled to room temperature. This method produces a peak hoop stress that decreases with decreasing temperature. The resultant hoop stress is calculated as:

$$\sigma_{H} = P * (ID+OD)/2t$$

Where σ_H is the hoop stress; ID and OD are the internal and external diameter respectively; and t is the wall thickness.

Ring Compression Testing and Three Point Bend Tests

Mechanical properties were determined using TPB and RCT. TPB and RCT were conducted at constant crosshead speeds of 5 mm/s. The crosshead speed was close to the maximum that the load frame was capable of achieving. For the RCT this translates into a nominal initial strain rate of 0.525 mm/mm/s. To evaluate the effects of strain rate initial tests were done at 0.05, 0.5 and 1mm/sec. There was no significant effect observed from the strain rate range other than an increase in yield stress with increasing rate for SRA ZIRLO.

The RCT samples were Wire Electrical Discharge Machined EDM to 8 mm in length. The samples where programed for a diametrical deflection of 1.7 mm initially to correspond to previous deflections used by other organizations but the deflection was increase to 2.2 mm to increase the ring strains and obtain data regarding failure points with larger deflections. The RCT and TPB test set ups can be seen in Figures 4 and 5.

The TPB tests used a span of 92 mm. The stationary supports were 3 mm diameter and the upper roller was 32 mm diameter. Preliminary efforts revealed that the tube had to be filled to avoid buckling and to more closely represent a loaded fuel rod condition. Quartz pellets 8 mm in diameter were cut to 12 mm lengths and loaded into the 8.38 mm ID tube. The ends were unconstrained and there was some gap between the ID of the tube and the OD of the pellets. The use of the quartz pellets do not fully replicate the pellet constraints and pellet to clad bonding impacts but are an incremental improvement over an open tube test. Initially the bend tests were set for a peak deflection of 6.35mm. Later tests were taken to larger deflections in order to produce unstable crack propagation in the bend samples.

The ring and bend DBTT testing was performed at temperatures ranging from room temperature to 200°C. This range encompasses temperatures predicted to exist at the time of handling and transport after interim long term storage.

RESULTS AND DISCUSSION

Hydride Reorientations in Samples

As a general trend it was observed that the hydride reorientation to a radial direction occurs relative to the degree of hoop stress applied. Figure 6 shows the effects of the differing hydrogen levels hydride morphology after aging at 170 MPa. Samples with 400 and 800 ppm have a denser circumferential (preexisting) hydride matrix and shorter radial hydrides compared to the 100 and 200 ppm samples. As the hydrides precipitate and grow in the higher hydrogen content samples the hydrides tend to extend existing hydrides which are mainly circumferential or for the radial hydrides they nucleate and grow between and not across circumferential hydrides. This characteristic of having proportionately more and longer radial hydrides in the 100 and 200 ppm samples has impacts on the RCT test results and will be discussed later.

The hydride structure in the samples with a 90 MPa RHGT all showed a circumferential structure with no significant radial hydride formation. Figure 7 is an example of the microstructure with 90 MPa RHGT.

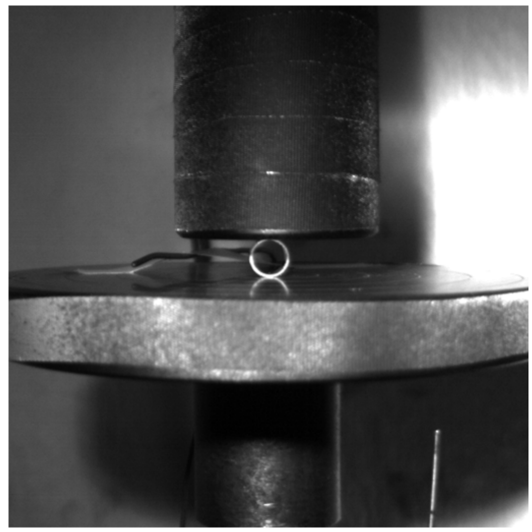


Figure 4 – Ring Compression Test Set Up

Figure 5 Three Point Bend Test Set Up

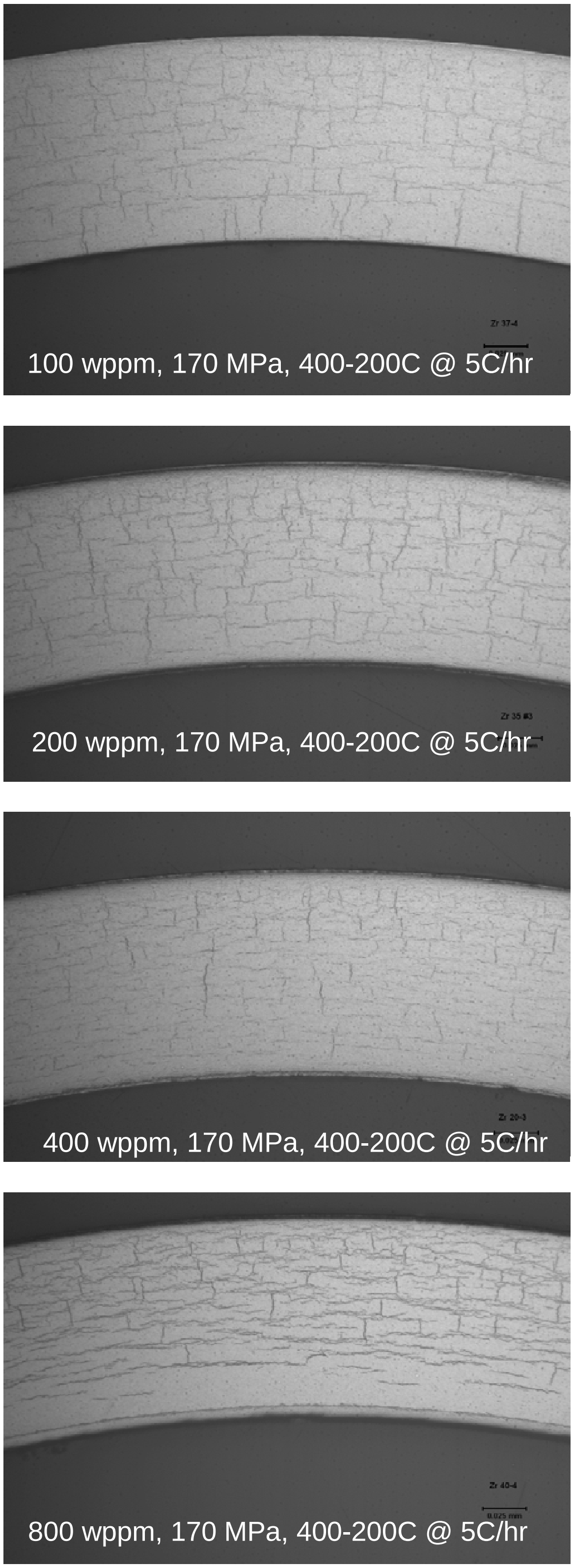


Figure 6 Hydride Structures Post Radial Hydride Growth Processing at 170 MPa Hoop Stress

Samples that were aged with a hoop stress of 130 MPa did show some radial hydride formation but less than the 170 MPa samples. Again, there were no observed radial hydrides in the 90 MPa samples.

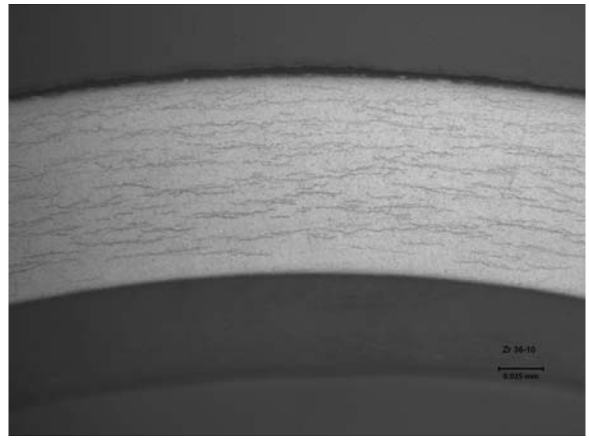


Figure 7 Hydride Structure in 100 ppm H sample with 90 MPa Hoop Stress – No significant radial hydrides

A general observation of the microstructures indicates that for the non-irradiated ZIRLO tubing tested there is no significant hydride reorientation observed with 90 MPA. At 130 MPa there is some radial hydride reorientation occurring and this effect is seen in the DBTT test data discussed later. At 170 MPa there is significant radial hydride formation and obvious effects on the strain tolerance in RCT tests (but not as strongly for the TPB test as discussed later).

To provide some degree of quantification regarding hydride reorientation, the technique of using a grid overlay was used. While there are some automated programs available than can be adapted to hydride orientation determination, the programs require calibrations and are affected by sample preparation. The use of an overlay is a relatively simple technique that can be easily adopted. The number of circumferential hydrides intercepting the grid lines is counted along with the number of radial hydride intercepts. The ratio of radial hydrides to circumferential hydrides is plotted as a function of the measured DBBT and is shown in Figure 8. With this relatively simple approach, the correlation between radial hydride density and DBTT is observed. It is not surprising that the DBTT increases with higher fractions of radial hydrides since these can act as crack starters and propagators.

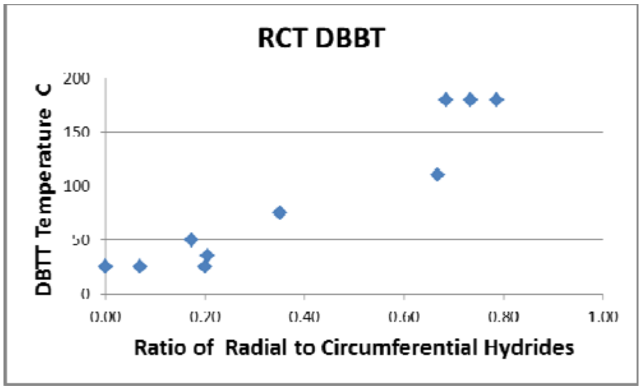


Figure 8 Correlation of the ratio of radial hydrides in the microstucture with DBTT

<u>RCT Data</u>

During the RCT testing the load-displacement data were recorded. As the displacement increases the load initially increases in an elastic manner and after sufficient deformation it becomes plastic. As shown in Figure 9, the initial maximum local stress/strain is at the N (north – 12 o'clock) and S (south – 6 o'clock) positions on the ID surfaces. Preliminary finite element data indicates that after a significant deflection the N and S positions begin to deform at the platens. The tube segments have observed to become concave and occasionally crack on the ID. The E – W positions on the OD surface then become the peak stress-strain areas.

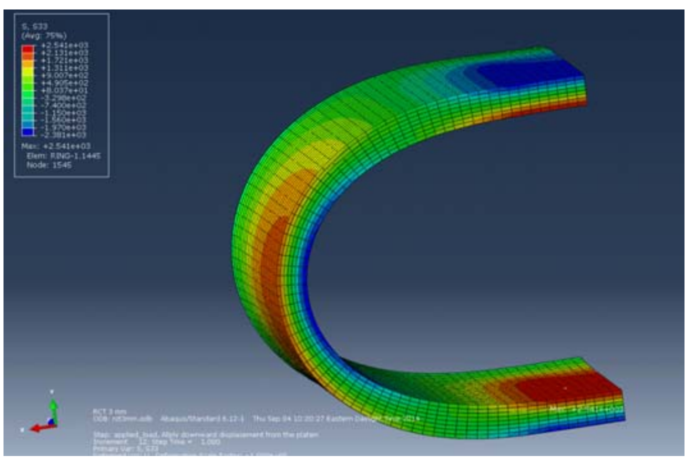


Figure 9 An example of FEA analysis of RCT test.

A typical set of RCT curves for samples charged with 400 ppm and with RGHT at 130 and 170 MP is shown in Figure 10. On the curves the areas of plastic yielding are seen when the curve deviates from the linear slope. An abrupt drop in the load is seen during displacement and is assumed to be associated with crack initiation/propagation. The plastic displacement at the load drop is used to determine the failure strain for the specific test condition.

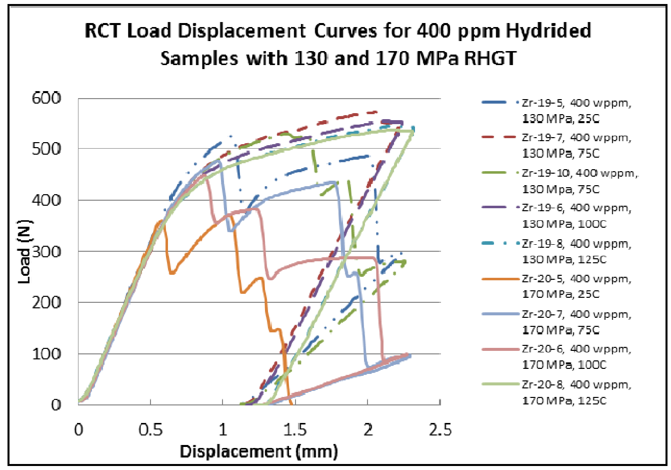


Figure 10 RCT Curves for 400 ppm H and 130/170 MPa Hoop Stresses

The RCT of the 100 ppm H loaded samples are shown in Figures 11, 12 and 13 and depict the effect of the hoop stress during radial hydride aging and the effect of the sample temperature in relative strain tolerance prior to crack formation and propagation. At the 90 MPA hoop stress all samples survived the programmed sample strain without failure indicating that for this set of conditions there is no significant radial hydride formation and that the ductility is retained even at room temperature. The absence of radial hydrides for the 90 MPa sample was also confirmed by the hydride characterization using grid overlay counting.

As expected as the hoop stress during RHGT increases, the amount of radial hydride reorientation increases and there is an associated reduction in strain tolerance versus test temperature. As shown in Figure 10, for the 400 ppm sample the 130 MPa sample survived the programed strain at 100°C but failed at 75°C while the 170 MPa sample survived at 125°C but failed at 100°C.

While the higher hoop stresses clearly have an adverse effect on the RCT strain tolerance there is a different trend associated with the hydrogen content. As seen in the comparison of the 170 MPa hoop stress results of the different samples, the greatest impact of the radial hydrides is observed in the lower hydrogen level samples, 100 and 200 ppm, where the temperature needs to be near 200°C to tolerate the test strain. For the 400 and 800 ppm samples a test temperature of 125°C results in equivalent strain tolerance. The data comparisons indicate that for the RCT type test the worst case condition is a high hoop stress and relatively low hydrogen content (100 -200 H ppm range). The reason is that at the low hydrogen levels as there is a significant fraction of freshly precipitated hydrides which tend to orient radially with high hoop stress. When a high fraction of undissolved circumferential precipitates remain (400 and 800 ppm samples) the radial hydrides are shorter in length (terminating when intersecting existing circumferential hydrides) and less dense ("memory effect" from existing circumferential hydrides) and thus, are more resistant to unstable radial crack (RCT type) propagation.

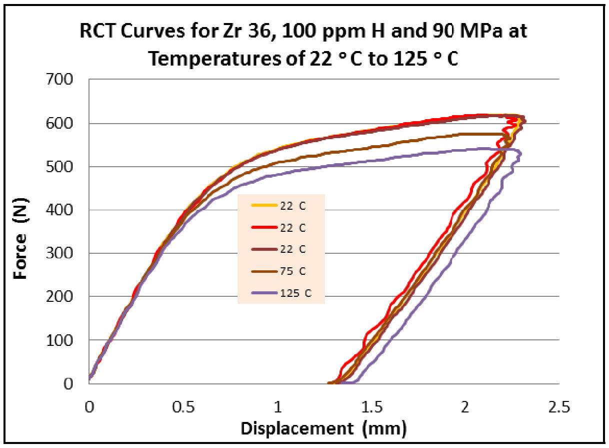


Figure 11 RCT Curves for 100 ppm H and 90 MPa RHGT

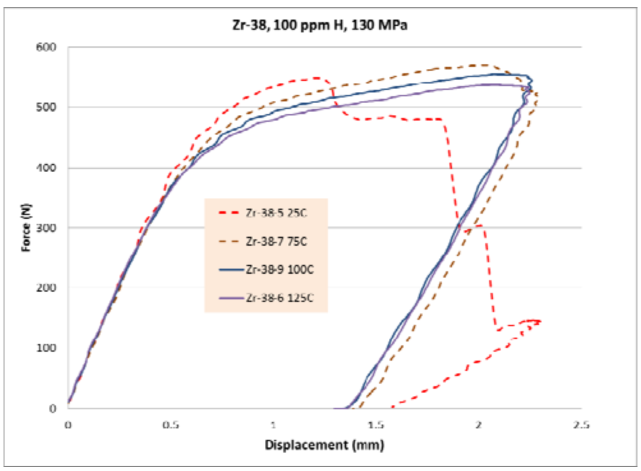


Figure 12 RCT Curves for 100 ppm H and 130 MPa

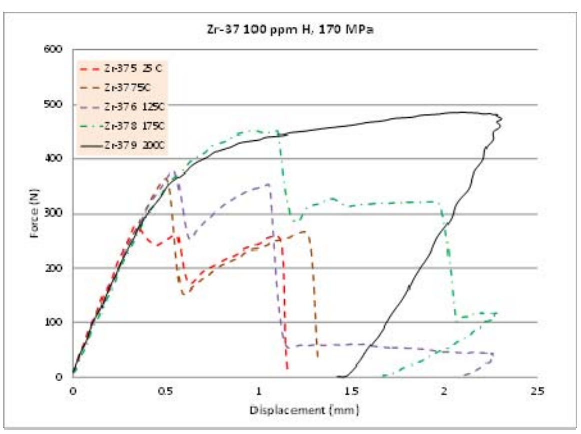


Figure 13 RCT Curves for 100 ppm and 170 MPa Hoop Stress

RCT DBTT and Mechanical Strain Calculations

The mechanical strain in the RCT tests is calculated as the percentage of the plastic deflection at failure / sample OD. Using the 25°C result of the 800 ppm / 170 MPa test as an example:

Calculated Elastic deflection at load drop = 0.6577
Sample OD = 9.5 mm
% strain = (1.075 – 0.6577)/9.5 x 100 = 4.4 %

Thus this sample is listed as having 4.4 % strain at failure. This is not the true strain but a relative plastic strain measurement. Subsequent FEA evaluations indicate that the peak strain is about 6.5% (elastic and plastic) for this deflection. For these calculations the elastic portion was assumed to be directly related to the loading modulus, i.e., the slope of the load/displacement during the initial loading, and not the unloading modulus since the tubes have experienced plastic deformation. The unloading modulus for RCT samples is lower than the loading modulus. This is postulated to be partially an effect of the ring sample acting as a mechanical spring and some setting occurring during plastic deformation. The use of the loading modulus to calculate the elastic strain reflects well the stain conditions that would be encountered during accident loading conditions and provides a consistent basis for relative comparisons. Using the above technique the failure strains associated with the various RCT tests were calculated. The strains for each set of test conditions were plotted as a function of the test temperature to determine the (quasi) DBTT. These comparison plots are shown in Figures 14 through Figure 16. Assuming a strain below 5% as being in the brittle area the transition temperature point was interpolated for each hydrogen level and RHGT combination. The choice of 5% in this specific case is based on the temperature and ductility profiles that show a knee at about 5%. To reiterate, the strain % is not the true strain in the material but rather a relative strain.

Figure 14 RCT DBTT at 90 MPa

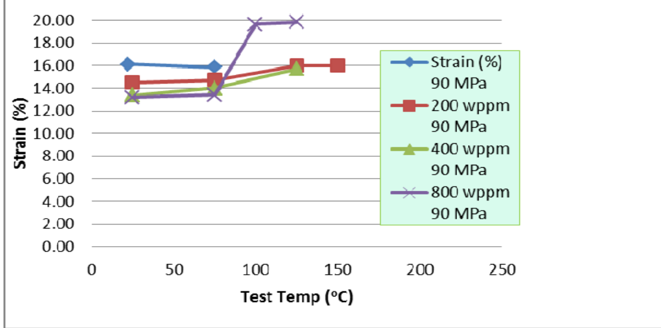


Figure 15 RCT DBTT at 130 MPa

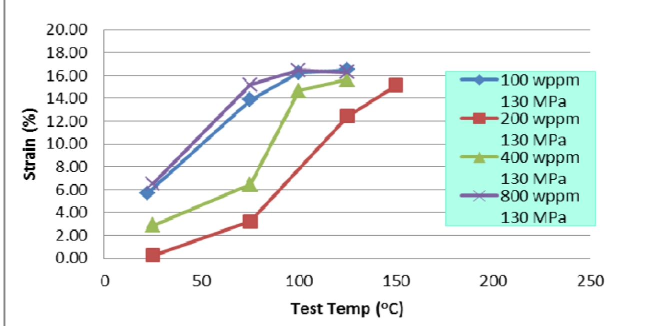
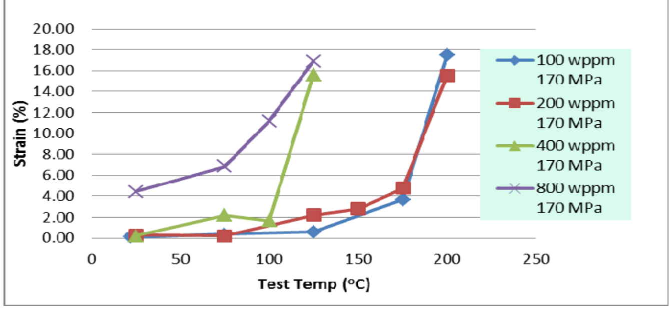


Figure 16 RCT DBTT at 170 MPa



Interpolation of the RCT transition temperatures are summarized in Table 1.

Table 1 Ring Compression Tests (Quasi-)DBTT

	RGHT Nominal Pressure (MPA)		
RHGT Hydrogen Level (PPM)	90	130	170
100	<RT	<RT	180°C
200	<RT	75°C	180°C
400	<RT	50°C	110°C
800	<RT	<RT	35°C

TPB Data

The initial bend samples were tested at the conditions noted in Table 2. Examples of load- displacement curves are shown in Figures 17 through 19

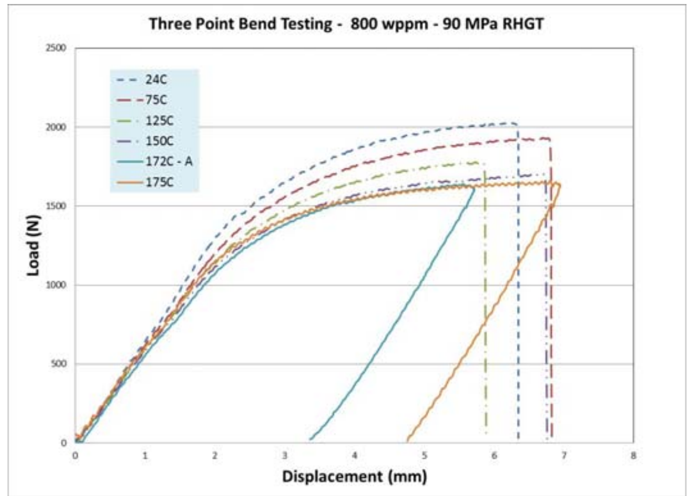


Figure 17 TPB Profile for 800 ppm hydrogen sample

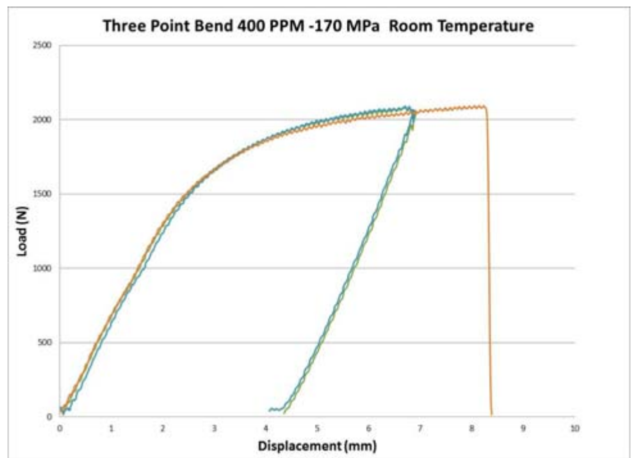


Figure 18 TPB profile for 400 ppm hydrogen sample

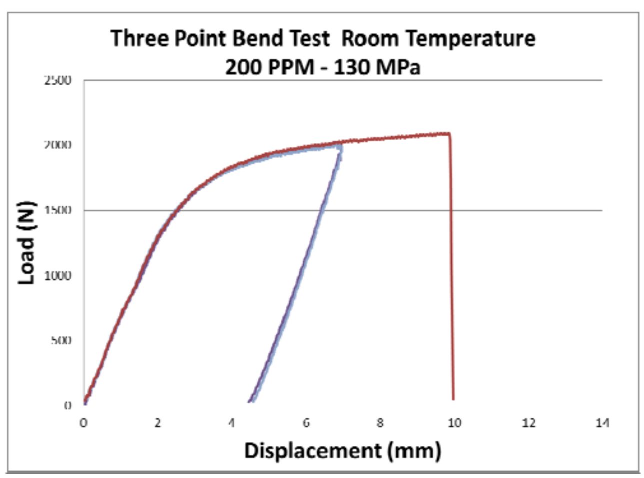


Figure 19 TPB profile for 200 ppm H sample

TPB DBTT results

The initial TPB test results were characterized by measuring the displacement at the point of failure / major load drop and comparing that value to a 14 mm displacement obtained from an as received tube. When additional test data becomes available then this relative comparison technique can be more refined. But this provides a basis to determine relative ductility. The calculated relative strain values are plotted in figure 20 and range from around 27 % to 65 %. These are not absolute strains but are relative values. The data point for the 200 ppm H / 130 MPa / 24°C indicates very high relative ductility (associated low DBTT) in the TPB test. This result is significantly different compared to the observations from the RCT type test which records this condition to have relatively low ductility and high DBTT. The 400 ppm H/ 170 MPa / 24°C test also indicates a relatively high ductility for the axial bend at room temperature versus the low ductility observed in the RCT test. In that same reverse trend the 800 ppm H TPB test samples show relatively low ductility while in the RCT tests the ductilities were relatively high for the 800 ppm H tests.

A proposal to explain the oposing DBTT impact trends with hydrogen levels and radial hydrides between RCT and TPB includes:

a) For RCT the crack plane is normal to the circumferential direction and moving radially.
b) For the TPB test the crack is normal to the axial direction and moving radially.
c) The radial hydride planes are parrelle to the RCT crack propogation and normal to the TPB crack propogation; thus, radial hydrides can be an enhancing factor for the RCT cracking but may not have a significant impact on TPB crack propogation.
d) The morphology of the circumferential hydrides relative to the axial and circumferential directions along with the grain structure may favor one type of crack propogation over another.

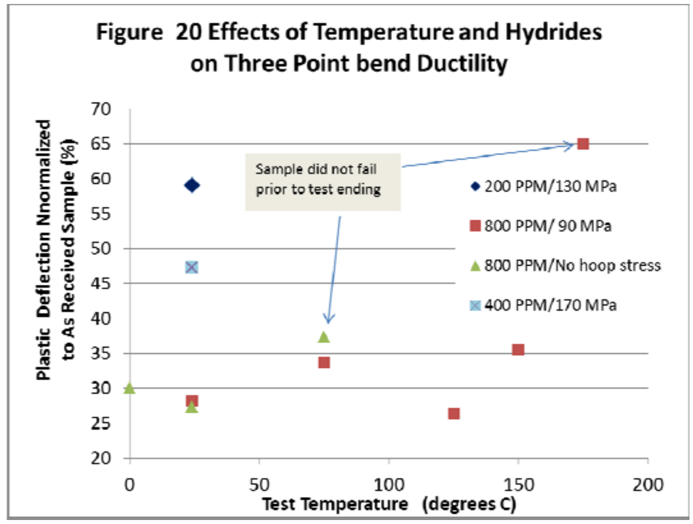


Figure 20 Effects of Temperature and Hydrides on Three Point bend Ductility

In reviewing the TPB data it is observed that:

A) For 200 ppm – 130 MPa sample there is relatively large ductility at 25°C compared to the RCT test which has a DBTT above 75°C.
B) For the 400 ppm – 170 MPa there is good ductility at 25°C whereas for the RCT test the DBTT is greater than 110C
C) For the 800 ppm tests with no significant radial hydriding temperatures of 150°C may be needed to have good ductility whereas for the RCT test the DBTT is room temperature.
D) The presence or absence of a hydride rim structure and its influence on ductility needs to be studied further.

CONCLUSIONS

1) For the test material and conditions examined there was no significant hydride reorientation observed for the 90 MPa RHGT with 400°C aging treatment. This is observed both in the microstructural hydride examinations and the mechanical ductility testing.
2) The RCT results indicate that for the cladding conditions tested and for Mode III pinch loading that a 90 MPa reorientation stress that a DBTT of room temperature is reasonable; for a 130 MPa initial hoop stress level a DBTT temperature of about 75°C exists and for 170 MPA the DBTT can exceed 175°C. Hydrogen level is a variable for DBTT and these temperatures represent worst case hydrogen conditions used in the tests. However, for most fuel rods there is a significant range (primarily axial but with some azimuthal) in clad hydrogen levels such that there is a reasonable probability of having a critical area somewhere along the fuel rod.

3) For the pinch stress- Mode III – RCT condition cladding areas with lower hydrogen levels of 100 – 400 ppm are more susceptible to elevated DBTT than sections with high hydrogen levels. The degree of impact is predicated on having a hoop stress where reorientation occurs.
4) The initial bend test results suggest that the DBTT for TPB conditions with 130 MPa hoop stress is below 25°C for hydrogen levels at and below 400 ppm and compares to a 75°C to 110°C DBTT for RCT under similar conditions. Whereas, for higher hydrogen levels towards 800 ppm the TPB DBTT at 90 MPa is about 150°C compared to the RCT DBTT at the same condition of room temperature.
5) For Mode I and II conditions of axial bending the initial data indicates that there is very little if any impact from relative radial hydride formation; thus, TPB is less sensitive to hoop stress and thermal cycling during fuel drying for storage. However, the clad sections with higher hydrogen levels have higher DBTT (less ductile) than sections with lower hydrogen.

ACKNOWLEDGMENTS

The authors would like to recognize Tony Curtis and Jacqueline Polz for their work on providing micrographs, Glenn Chapman for his efforts for the mechanical property testing, Poh-Sang Lam for the finite element analysis, Savannah River National Laboratory for funding this activity as a Laboratory Directed Research and Development project, and the Department of Energy for funding this work under contract DE-AC09-08SR22470

REFERENCES

1) “Used Nuclear Fuel Characteristics at End of Life” Kesterson, R.L Sindelar, R.L., Vinson, D. FCRD-UFD-2013-000130 March 29, 2013
2) “Hydrogen Pickup and Redistribution in Alpha-Annealed Zircaloy-4” ,Kammenzind, et al;; ASTM STP 1295, pages 338-370, 1996
3) “In situ study of hydride precipitation kinetics and re-orientation in Zircaloy using synchrotron radiation” K.B. Colas, A.T. Motta, J.D. Almer, M.R. Daymond, M. Kerr, A.D. Banchik, Vizcaino, J.R. Santisteban, Acta Materialia 58 (2010) 6575–6583
4) “A Method for Determining the Spent-Fuel Contribution to Transport Cask Containment Requirements,” T. L. Sanders, K. D. Seager, Y. R. Rashid, et al SANDIA Report, SAND90- 2406, TTC-1019, UC-820, November 1992.
5) “The Adsorption of Hydrogen on Low Pressure Hydride Materials” Gregg A. Morgan, Jr.* and Paul S. Korinko, Conference Proceedings, Material Science and Technology 2011, October 16-20, 2011, Columbus, OH.