# Post-Quench Ductility at 135˚C for 17×17 ZIRLO Cladding Oxidized at 1200˚C, Slow Cooled to 800˚C and Quenched

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## Summary

Ring-compression test results have been reported for as-received 17×17 ZIRLO [1] oxidized at 1200˚C, slow cooled to 800˚C, quenched, and compressed at room-temperature (RT) and a displacement rate of 0.033 mm/s (0.35%/s). The ductile-to-brittle transition ECR was determined to be <13% based on these RT tests. The ductility criteria used in this work are: ≥3% offset strain prior to the first through-wall crack implies ductile behavior; <3% offset strain requires direct measurement of the change in ring diameter along the loading direction to determine permanent displacement and strain; and ≥1% permanent strain implies ductile behavior. Samples with <1% permanent strain are classified as brittle.

Consistent with the ANL Test Plan, cladding alloys that exhibit brittle behavior at RT and <17% ECR are retested at post-LOCA-quench temperatures of 135˚C (short-time post-LOCA core temperature) and 100˚C (longer-time post-LOCA core temperature). Ductility at 135˚C would satisfy the LOCA embrittlement criteria for the quench phase of the LOCA. Ductility at 100˚C would satisfy the embrittlement criteria for postulated post-quench events (e.g., seismic. The results of ring-compression tests conducted at 135˚C are summarized in this report.

Additional rings were cut from the same oxidized samples reported in Ref. 1. After cutting off the oxidized ends, the rings were ≈5-mm-long. Although the reference ring length is 8 mm, previous benchmarking had shown no difference in ductility for sample lengths in the range of 5 to 10 mm. The target ECR values for these samples, based on the Cathcart-Pawel (CP) weight gain correlation, were 10%, 15% and 17%. The corresponding ECR values based on measured weight gain are 10.3%, 15.4% and 17.8%. The results of the new tests, along with the previously published room-temperature results for ZIRLO rings, are summarized in Table 1 and shown in Figs. 1 (offset strain) and 2 (permanent strain) vs. measured ECR. Load-displacement curves for the new tests are given in the Appendices: A (RT tests with new samples -- to be conducted); B (100˚C with new samples -- to be conducted); and C (135˚C tests on previously oxidized samples). The offset strain is ≥7% for measured ECR ≤ 18%, for CP-calculated ECR ≤ 17% and for Baker-Just calculated ECR ≤ 22%. Therefore, at 135˚C, as-received ZIRLO satisfies the LOCA embrittlement criteria for the quench phase of LOCA. The difference between the test temperature (1200˚C) and the licensing PCT (1204˚C) is insignificant as the temperature variation around the test samples during steam oxidation is ≈ ±5˚C.

New 1200˚C-oxidized ZIRLO samples will be prepared with 10, 13 and 17% ECR for ring-compression testing at RT (0.35%/s), 100˚C (0.35 and 3.5%/s), and 135˚C (0.35 and 3.5%/s).

Table 1 Ring Compression Test Results for 17×17 ZIRLO Cladding Oxidized at 1200˚C, Slow-cooled to 800˚C, and Quenched. Room-temperature (RT) tests were performed on ≈8-mm-long rings at 0.0333 mm/s displacement rate (0.35%/s diametral strain rate) [1]. Tests were also performed on ≈5-mm-long rings at 135˚C and 0.35%/s. Nominal dimensions of as-received cladding are 9.50-mm OD and 0.57-mm wall thickness.

| Test Conditions | | ECR % | | Plastic Displacement, mm | | Plastic Strain, % | |
|---|---|---|---|---|---|---|---|
| T, ˚C | Strain Rate, %/s | CP | Meas. | Offset | Permanent | Offset | Permanent |
| RT | 0.35 | 4.9 | 4.8 | >5.55 | >5.24 | >58 | >53 |
| RT<br>135 | 0.35<br>0.35 | 10.0<br>10.0 | 10.3<br>10.3 | 0.26<br>>4.8 | 0.13<br>>4.8 | 2.7<br>>51 | 1.4<br>>51 |
| RT | 0.35 | 13.0 | 13.4 | 0.114 | 0.07 | 1.2 | 0.7 |
| RT<br>135 | 0.35<br>0.35 | 15.1<br>15.1 | 15.4<br>15.4 | 0.175<br>1.73 | 0.11<br>1.28 | 1.8<br>18.2 | 1.2<br>13.4 |
| RT<br>135 | 0.35<br>0.35 | 17.1<br>17.1 | 17.8<br>17.8 | 0.163<br>0.660 | 0.06<br>--- | 1.0<br>7.0 | 0.6<br>--- |
| RT | 0.35 | 21.2 | 22.3 | 0.108 | 0.06 | 1.1 | 0.6 |

## References

1. Y. Yan, T. Burtseva and M. C. Billone, "Post-Quench Ductility Results for Zry-4 and ZIRLO Oxidized at 1200˚C, Slow Cooled to 800˚C and Quenched," ANL letter report to NRC and Westinghouse, March 23, 2004.

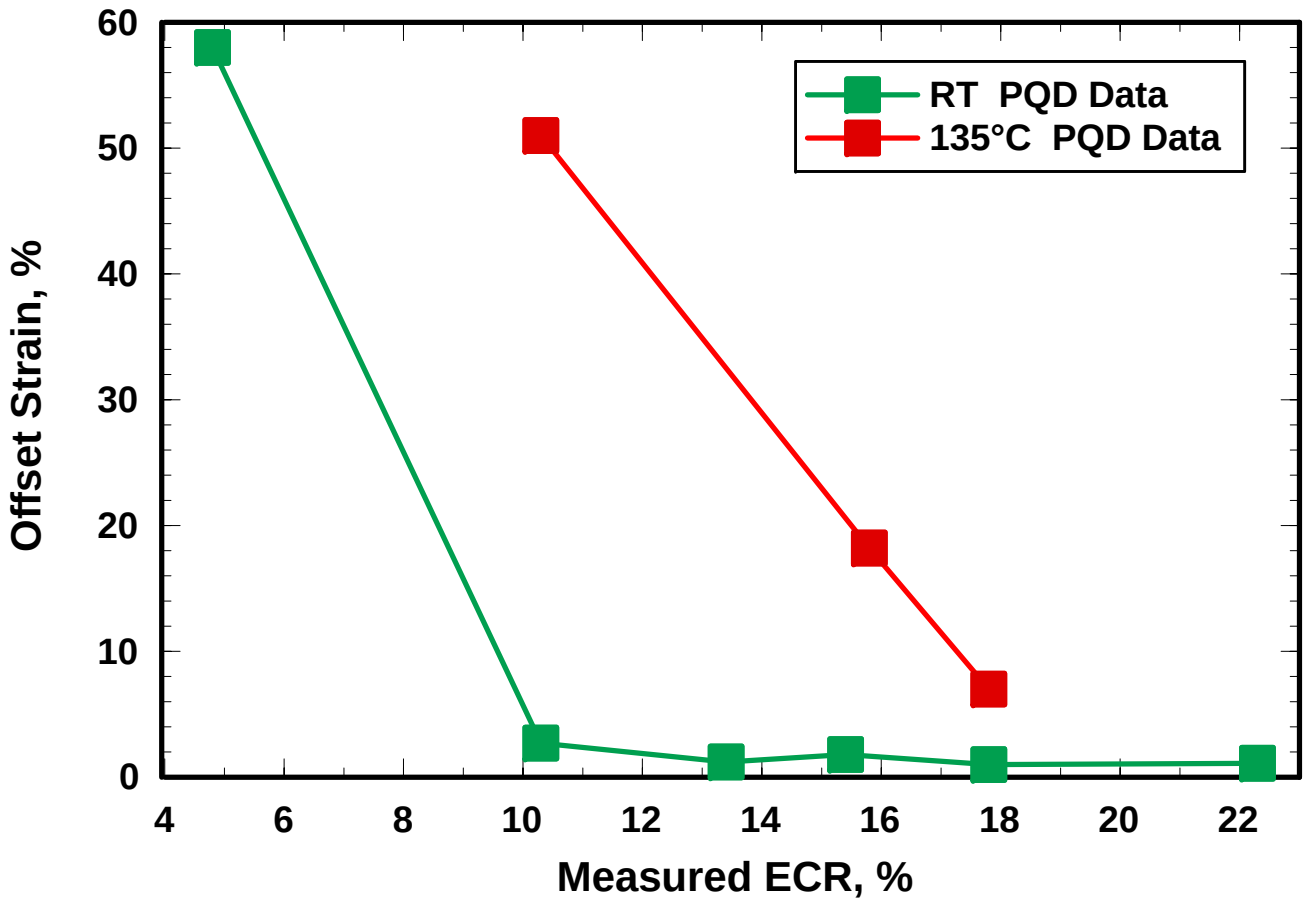


Fig. 1. Offset strain vs. measured ECR for 17×17 ZIRLO (9.50-mm OD, 0.57-mm wall thickness) oxidized at 1200˚C, slow-cooled to 800˚C and quenched. The results are from ring-compression tests conducted on ≈8-mm-long rings at room temperature (RT) and a displacement rate of 0.0333 mm/s (0.35%/s) and on ≈5-mm-long samples at 135˚C and 0.35%/s. Offset strain is a measure of ductility obtained from the load-displacement curves by subtracting the elastic displacement from the total displacement and normalizing to 9.50 mm.

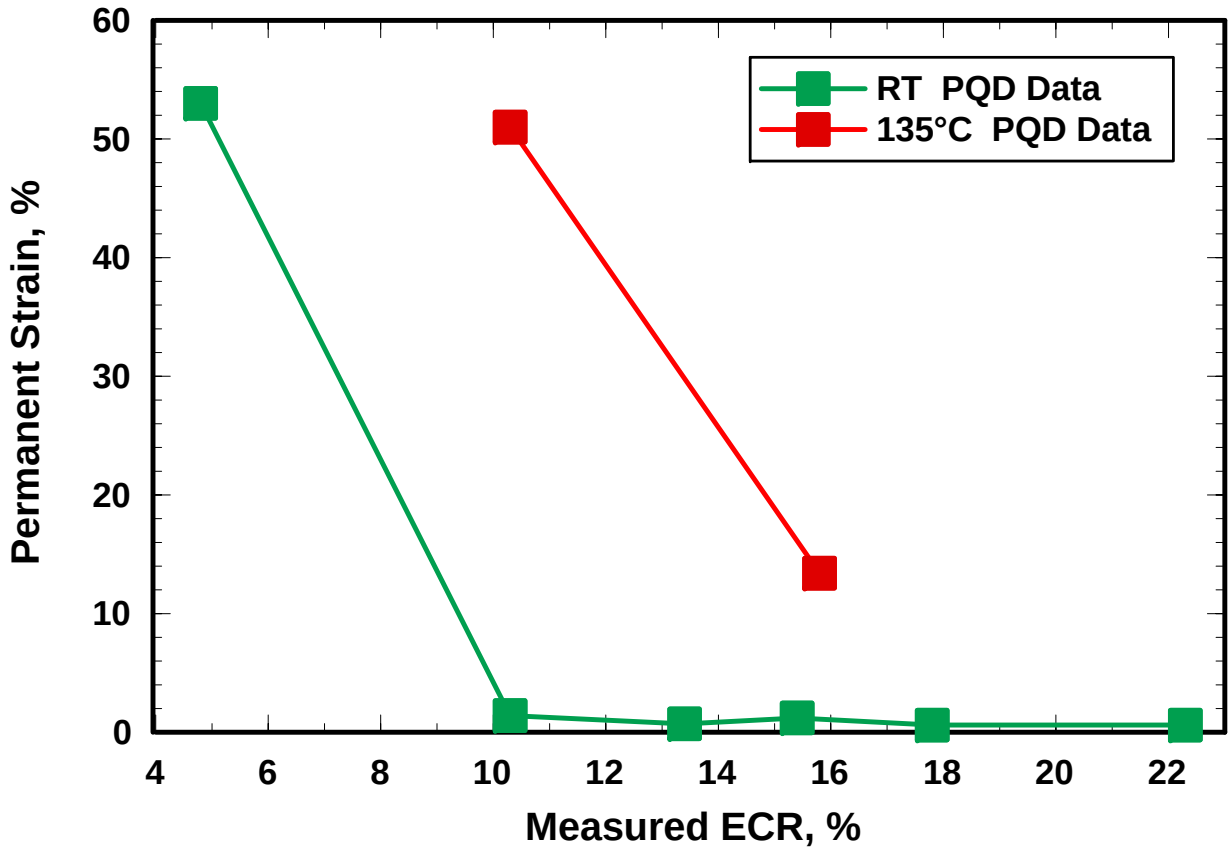


Fig. 2. Permanent strain vs. measured ECR for 17×17 ZIRLO (9.50-mm OD, 0.57-mm wall thickness) oxidized at 1200˚C, slow-cooled to 800˚C and quenched. The results are from ring-compression tests conducted on ≈8-mm-long rings at room temperature (RT) and a displacement rate of 0.0333 mm/s (0.35%/s) and on ≈5-mm-long rings at 135˚C and 0.35%/s. Permanent strain is a direct measure of ductility obtained from the difference between measured pre- and post-test diameters (along the loading direction) normalized to 9.50 mm.

## APPENDIX A

**Load-Displacement Curves for 1200˚C-Oxidized and Quenched ZIRLO Samples Subjected to Ring-Compression Tests at Room Temperature and a Cross-Head Displacement Rate of 2 mm/minute**

**(Tests on new 10, 13, and 17% ECR samples are "to be conducted.")**

## APPENDIX B

**Load-Displacement Curves for 1200˚C-Oxidized and Quenched ZIRLO Samples Subjected to Ring-Compression Tests at 100˚C and Cross-head Displacement Rates of 2 mm/minute and 20 mm/minute**

**(Tests on new 10, 13, and 17% ECR samples are "to be conducted.")**

## APPENDIX C

**Load-Displacement Curves for 1200˚C-Oxidized and Quenched ZIRLO Samples Subjected to Ring-Compression Tests at 135˚C and a Cross-head Displacement Rate of 2 mm/minute**

**(Tests on new 10, 13, and 17% ECR samples are "to be conducted" at 2 and 20 mm/minute.)**

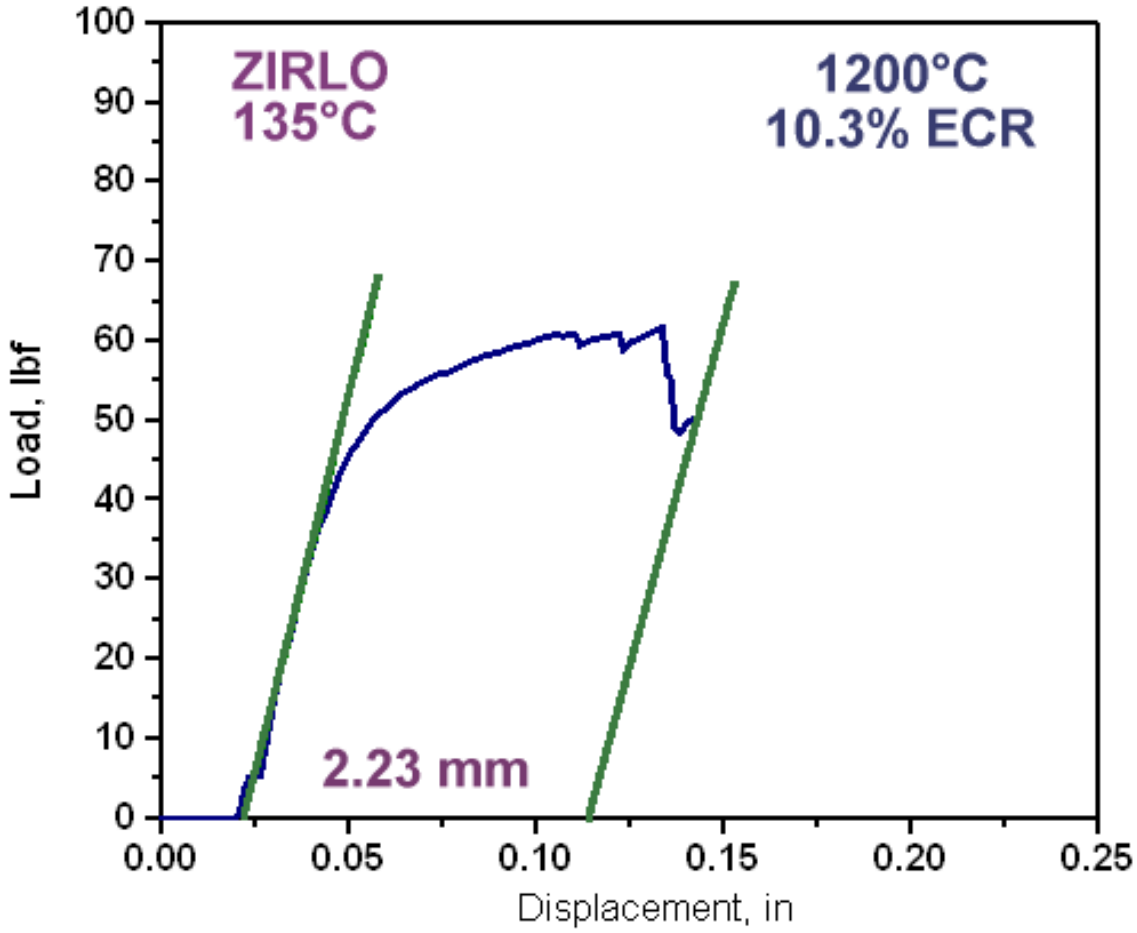


Fig. C.1a Load-displacement data for 4.62-mm-long ZIRLO ring oxidized at 1200˚C to 10.3% measured ECR. Ring-compression test was conducted at 135˚C and 0.0333 mm/s displacement rate. Load drop is due to cracking of the oxide layers at the top and bottom of the ring. No through-wall failure was observed after offset and permanent displacements of 2.23 mm. Note: a reliable measurement of permanent displacement could not be obtained because of the oxide spallation at the top and bottom of the ring.

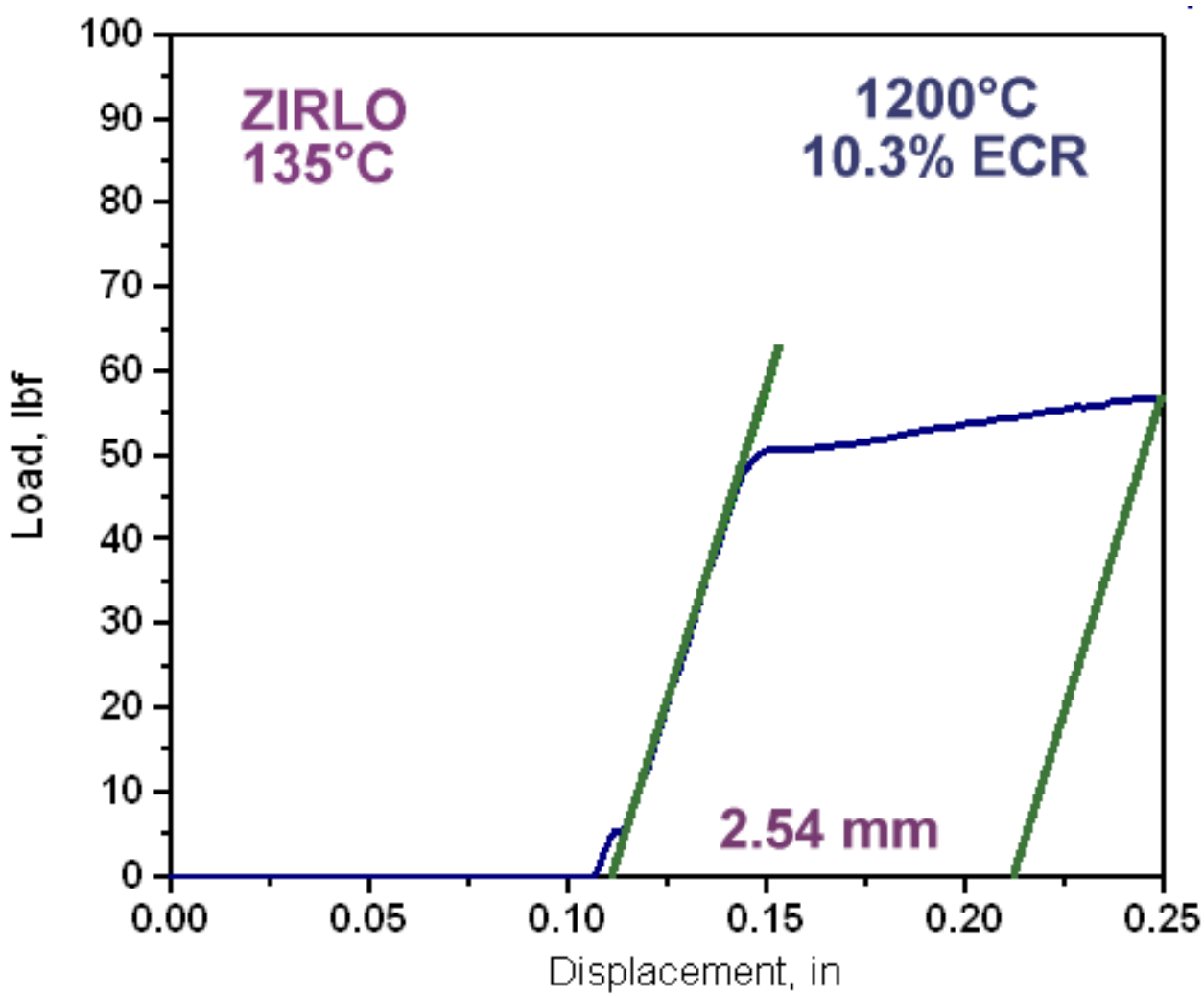


Fig. C.1b Load-displacement data for the second loading cycle of a 4.62-mm-long ZIRLO ring oxidized at 1200˚C to 10.3% measured ECR. Ring-compression test was conducted at 135˚C and 0.0333 displacement rate. No through-wall failure was observed after additional offset and permanent displacements of 2.54 mm and 2.66 mm, respectively.

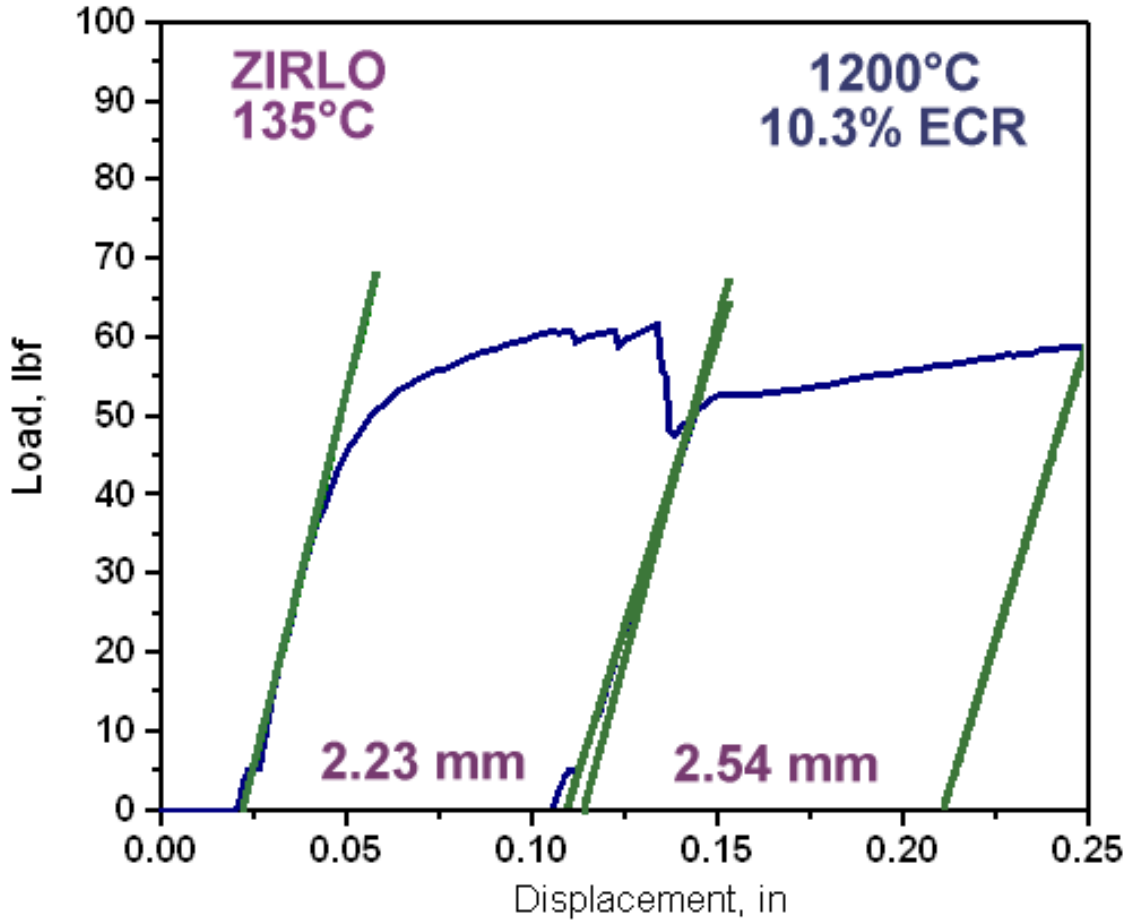


Fig. C.1c Composite load-displacement data for two-cycle loading of a 4.62-mm-long ZIRLO ring oxidized at 1200˚C to 10.3% measured ECR. Ring-compression test was conducted at 135˚C and 0.0333 mm/s displacement rate. No through-wall failure was observed after total offset and permanent displacements of 4.77 mm and 4.88 mm, respectively. Note: the offset displacement is more reliable for this case because of oxide spallation at the top and bottom surfaces of the ring.

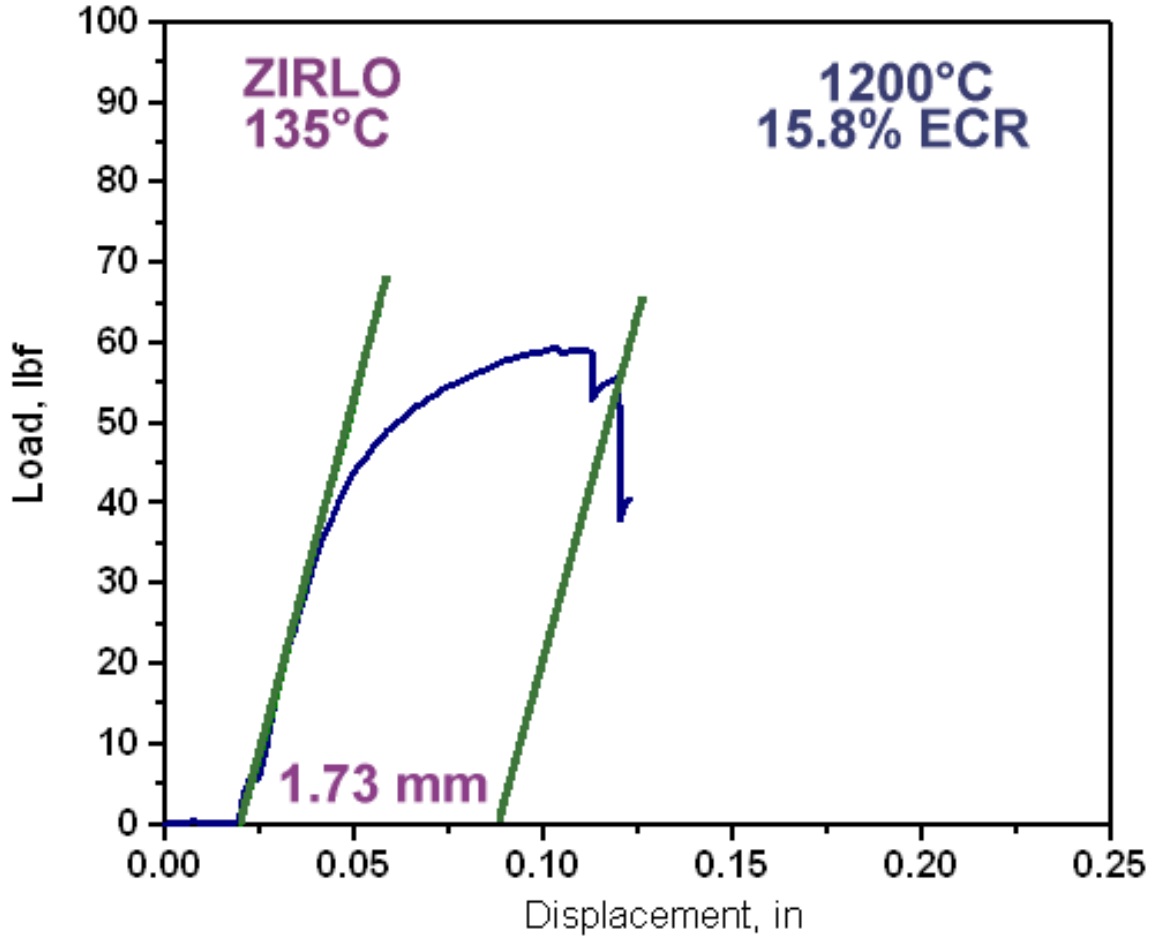


Fig. C.2 Load-displacement data for 4.90-mm-long ZIRLO ring oxidized at 1200˚C to 15.8% measured ECR. Ring-compression test was conducted at 135˚C and 0.0333 mm/s displacement rate. A single through-wall crack was observed at the bottom of the sample (support surface). Offset displacement prior to failure is 1.73 mm. Permanent displacement based on pre-test minus post-test diameter measurement along loading line is 1.28 mm.

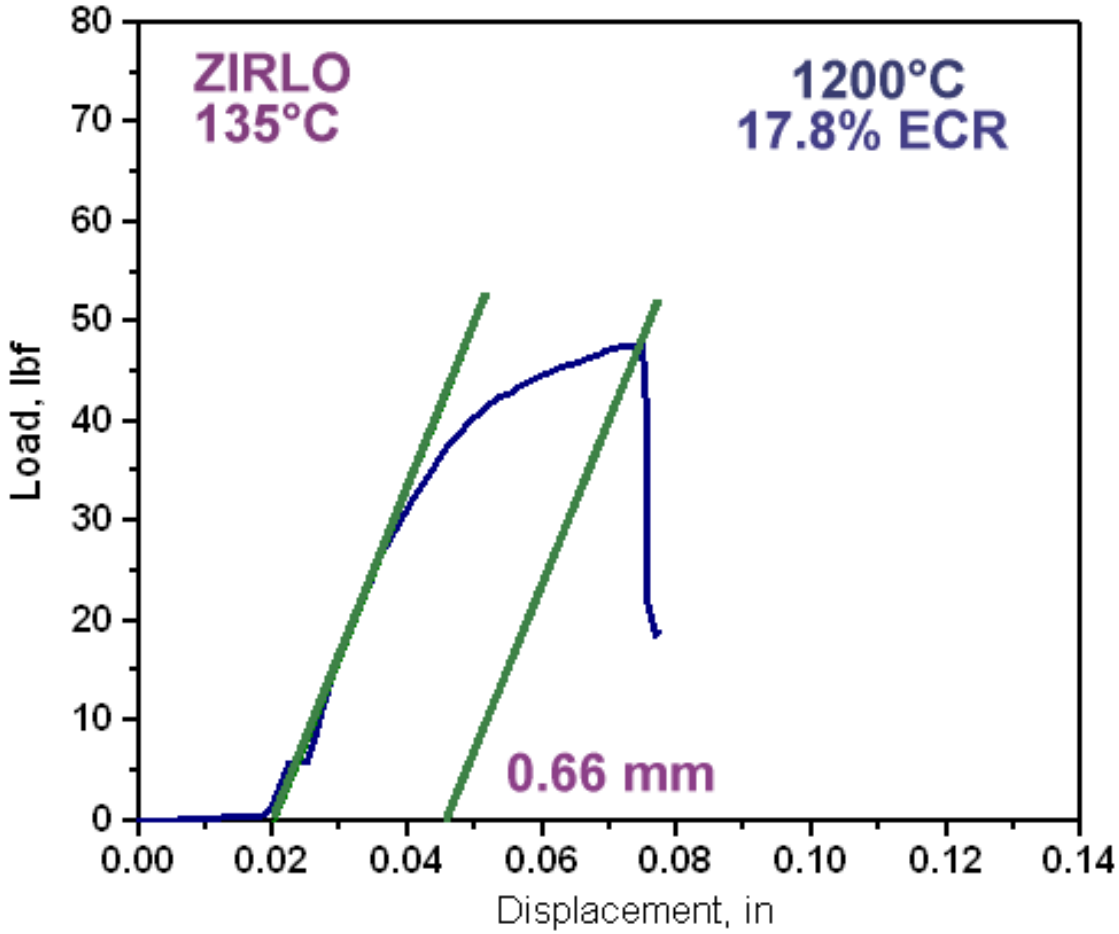


Fig. C.3 Load-displacement data for 5.05-mm-long ZIRLO ring oxidized at 1200˚C to 17.8% measured ECR. Ring-compression test was conducted at 135˚C and 0.0333 mm/s displacement rate. Through-wall cracks were observed at the top (loading surface) and bottom (support surface) of the sample. Offset displacement prior to failure is 0.66 mm. Permanent displacement based on pre-test minus post-test diameter measurement along loading line could not be determined from this sample.