Argonne Results for ANL-Studsvik Benchmark Tests

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Summary

Prior to installing the LOCA apparatus into a hot cell, Studsvik will perform two sets of benchmark tests. The conditions for the LOCA tests are: 1200-psig (82.8-bars) fill pressure at 300°C, 5°C/s heating ramp from 300°C to 1200°C, 86-s hold time at 1200°C, 3°C/s cooling rate to 800°C, and quench at 800°C. The bend-test conditions are: 1mm/s displacement rate, 14-mm maximum displacement, and 30°C (or whatever room temperature is) sample temperature.

Based on 11 tests conducted by ANL with 1200-psig fill pressure, the anticipated rupture temperature (T_R), circumferential rupture strain ($\Delta C_m/C_{mo}$) and pre-oxidation wall thickness (h_f) are 750±7°C, 44±4%, and 0.40±0.1 mm, respectively, where the ± values represent one-standard deviations. For 1200°C hold temperature, the oxidation level should be 17.0±0.5% CP-ECR. The control thermocouple (TC) is maintained at 1200°C, but the other TC (180° from control TC) may read higher or lower depending on its circumferential orientation relative to the rupture opening. The CP-ECR is recalculated after the test is completed based on measured rupture strain and measured temperatures. To the nearest percent, the expected CP-ECR is 17±1%. The reason that two LOCA tests are conducted is to determine if the results are reproducible within the expected scatter. Two bend tests are conducted for a similar reason. In particular, it is of interest to determine if both bend samples sever across the rupture opening as opposed to locations between the rupture tip and the location of the hydrogen peak. Bend-test data include load-displacement curves and performance metrics determined from these curves: maximum bending moment (strength), failure energy (toughness), and offset displacement (measure of plastic displacement). Post-bend-test characterization includes measurement of the outer-surface oxide thickness (at the rupture node center) to validate the recorded temperatures and measurement of the hydrogen-content profile. The results will be compared to ANL results generated under the same LOCA- and bend-test conditions.

ANL has completed the benchmark tests described above. Tables 1 and 2 list the results of all ANL LOCA and bend tests conducted with as-fabricated ZIRLO. The specific benchmark tests are listed in Table 2 as OCZL#25, OCZL#29, and OCZL#32. Because of the differences between ANL and Studsvik temperature controllers, the ANL hold time was reduced from 86 s to 65 s to achieve the sample CP-ECR. The bend-test temperature for the OCZL#25 and #29 samples was 135°C, consistent with all previous ANL bend tests conducted. The bend-test temperature for the OCZL#32 sample was 30°C to determine the effects of test temperature on performance metrics and to allow direct comparison to Studsvik results. The measured rupture strains (42%, 49% and 49%, respectively) were within the expected range (see Fig. 1). Using these strains to calculate wall thickness, along with measured temperature profiles, the calculated CP-ECR values were 16%, 17%, and 16%, respectively. It should be noted that the OCZL#25 sample failed at two locations outside the rupture opening while the OCZL#29 sample severed at

the axial location through the center of the rupture opening. Bending of the OCZL#32 sample also resulted in severing along the cross section centered with respect to the axial span of the rupture opening.

Based on one-to-one comparisons, the maximum bending moment (6.7 N•m) for the 30°C test was between the 8.3 N•m for the OCZL#25 sample (higher strength, no measurable plastic displacement) and the 4.7 N•m for the OCZL#29 sample (lower strength, large plastic displacement). However, the 30°C bend sample failure energy of 0.26 J was lower than the failure energies (0.50 and 0.40 J) of the 135°C bend samples. It is not clear if these differences in strength and toughness are significant when data trends and data scatter are taken into account. Figure 2 shows the complete ANL data set for maximum bending moment vs. oxidation level. The 30°C bend-test data point lies close to the trend line. Figure 3 shows the normalized maximum energy. The 30°C bend-test data point lies close to, but below, the trend line in a region where failure energies are small.

At 16% CP-ECR, the severed cross section should by microscopically and macroscopically brittle at 30°C based on ring-compression test results. At 17% CP-ECR, the severed cross section clearly transitions from brittle (rupture edges) to ductile (more than half the cross section) material. It would be interesting to do SEM (scanning electron microscopy) fractography of these two severed cross sections to confirm these hypotheses and observations.

The two Studsvik 30°C data points will be added to Figs. 2 and 3. Based on ANL experience, the maximum bending moment and failure energy determined by Studsvik should be close to the trend lines shown in these figures.

It would be useful to have LOCA- and post-LOCA-bend test data for pre-hydrided (350±50 wppm) ZIRLO prior to conducting the Studsvik high-burnup tests. Based on ring-compression tests, high-burnup ZIRLO with 340-wppm hydrogen was brittle after oxidation to 8% CP-ECR with a peak oxidation temperature of 1190°C. The recommended hold temperature for the high-burnup ZIRLO integral tests to be conducted by Studsvik is 1050°C. At the lower oxidation temperature, ZIRLO with 350-wppm hydrogen should be ductile after 8% oxidation level. The dataset for pre-hydrided ZIRLO would be focused on a narrower oxidation level of 10±2%. Bend tests would be conducted at 135°C (reference conditions) and 30°C (as guidance for Studsvik). The dataset for pre-hydrided ZIRLO would be useful not only for determining the target oxidation levels (i.e., hold times) for the Studsvik tests. The results would also be used to determine the decrease in oxidation level required for high-burnup ZIRLO to achieve the same strength and failure energy as was realized for as-fabricated ZIRLO oxidized to 17% CP-ECR.

Table 1. Summary of results for LOCA integral and post-LOCA bend tests with as-fabricated ZIRLO cladding. The reference LOCA test conditions are: 1200-psig pressure at 300°C, 5°C/s heating rate to 1200°C, 1200°C hold temperature, 3°C/s cooling rate to 800°C, and quench at 800°C. Samples OCZL#8-11 are from ramp-to-burst tests that were slow-cooled without quench.

Test ID OCZL#	Fill Pressure, psig	Rupture Strain, % (T_R, °C)	CP-ECR %	Quench at 800°C	Stress in Rupture Node	Failure Location	Maximum Bending Moment N•m	Maximum Energy J	Plastic Displ. mm
6	1200	41 (750±30)	18	No	---	---	---	---	---
7	800	**22** (810±30)	16	No	---	---	---	---	---
8	600	19 (845±25)	0	No	Maximum tension	No cracking	20.9	>8.4	>7.7
9	400	33 (875±15)	0	No	Maximum tension	No cracking	20.6	>8.3	>7.7
10	1600	68 (715±10)	0	No	Maximum tension	No cracking	19.5	>7.7	>7.1
11	1400	**40** (≈750)	0	No	---	---	---	---	---
12	1000	31 (805±20)	14	No	Maximum compression	-40 mm +33 mm	10.5	0.78	0
13	1200	41 (741±15)	14	No	Maximum tension	Rupture opening	8.8	0.58	0
14	1200	46 (735±6)	18	Yes	Maximum tension	Rupture opening	5.7	0.24	0
15	1200	50 (755±23)	18	Yes	Maximum compression	Cracking; no failure	8.9	>2.3	>13
17	1200	47 (750±17)	13	Yes	Maximum tension	Rupture opening	8.4	0.71	> 6.3
18	1200	**43** (748±4)	12	Yes	Maximum tension	Rupture opening	13.5	1.29	0

Table 2. Additional LOCA integral and post-LOCA bend tests with as-fabricated ZIRLO cladding. Reference LOCA conditions for these tests were: 600-psig or 1200-psig fill pressure at 300°C, 5°C/s heating rate to 1200°C, 1200°C hold temperature, 3°C/s cooling rate to 800°C, and quench at 800°C. Reference conditions for bending tests were 2 mm/s displacement rate to 14-mm maximum displacement. The displacement rate was lowered to 1 mm/s after the OCZL#21 bend test to more closely approximate ring-compression maximum strain rate and axial-bend maximum strain rate.

Test ID OCZL#	Fill Pressure, psig	Rupture Strain, % (T_R, °C)	CP-ECR %	Quench at 800°C	Stress in Rupture Node	Failure Location	Maximum Bending Moment N•m	Maximum Energy J	Plastic Displ. mm
19	600	23 (840±12)	17	Yes	Maximum tension	+23 mm -23 mm	5.7	0.23	0
21	600	25 (850±10)	10	Yes	Maximum tension	+33 mm -29 mm	13.8	1.17	0
22[a]	600	20 (837±12)	11	Yes	Maximum tension	+25 mm -27 mm	11.1	0.83	0
25[a]	1200	**42** (757±21)	16	Yes	Maximum tension	-26 mm +26 mm	8.3	0.50	0
26	1200	31 (765±39)	16	Yes	---	---	---	---	---
27	1200	38 (760±23)	17	Yes	---	---	---	---	---
29[a]	1200	**49** (746±19)	17	Yes	Maximum tension	Rupture opening	4.7	0.40	>8.5
30	1200	**42** (746±19)	16	Yes	Unknown[b]	-28 mm +48 mm	---	---	---
32[a,c]	1200	**49** (748±8)	16	Yes	Maximum tension	Rupture opening	6.7	0.26	0

[a]Displacement rate lowered to 1 mm/s for better agreement between bend and ring-compression tests maximum elastic strain rate.
[b]Sample failed at two locations during disassembly.
[c]Bend test conducted at 30°C.

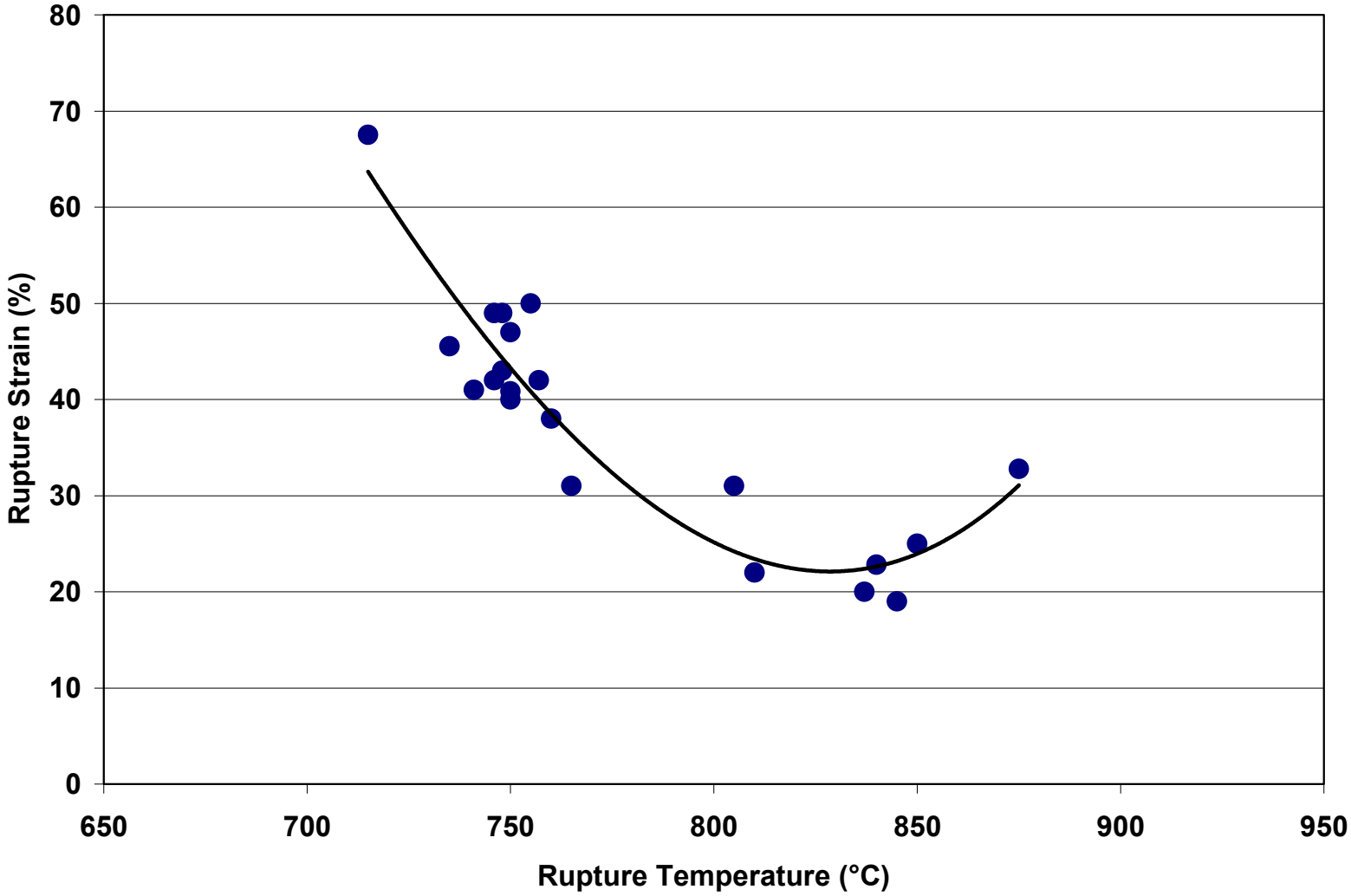

Fig. 1. Rupture strain as a function of rupture temperature for as-fabricated ZIRLO with fill pressures of 400 to 1600 psig at 300°C subjected to a temperature ramp of 5°C/s. Rupture strain is defined as the percent increase in mid-wall circumference following rupture and slow-cooling to room temperature.

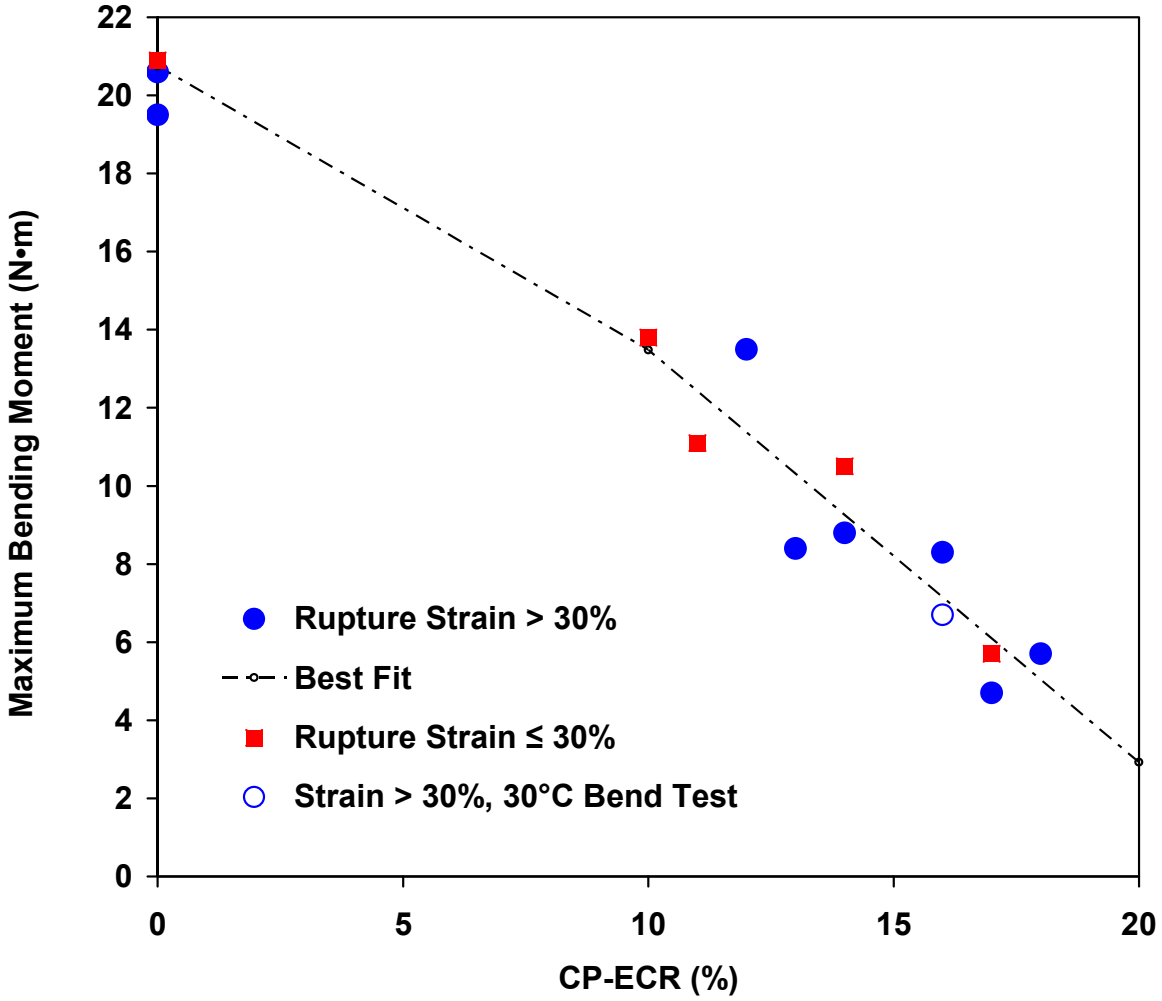

Fig. 2. Maximum bending moment as a function of oxidation level (CP-ECR) for post-LOCA samples subjected to four-point bending with the rupture region in tension for all tests but one. Bend tests were performed at 135°C and 2 or 1 mm/s to 14-mm maximum displacement. As indicated, one bend test was conducted at 30°C.

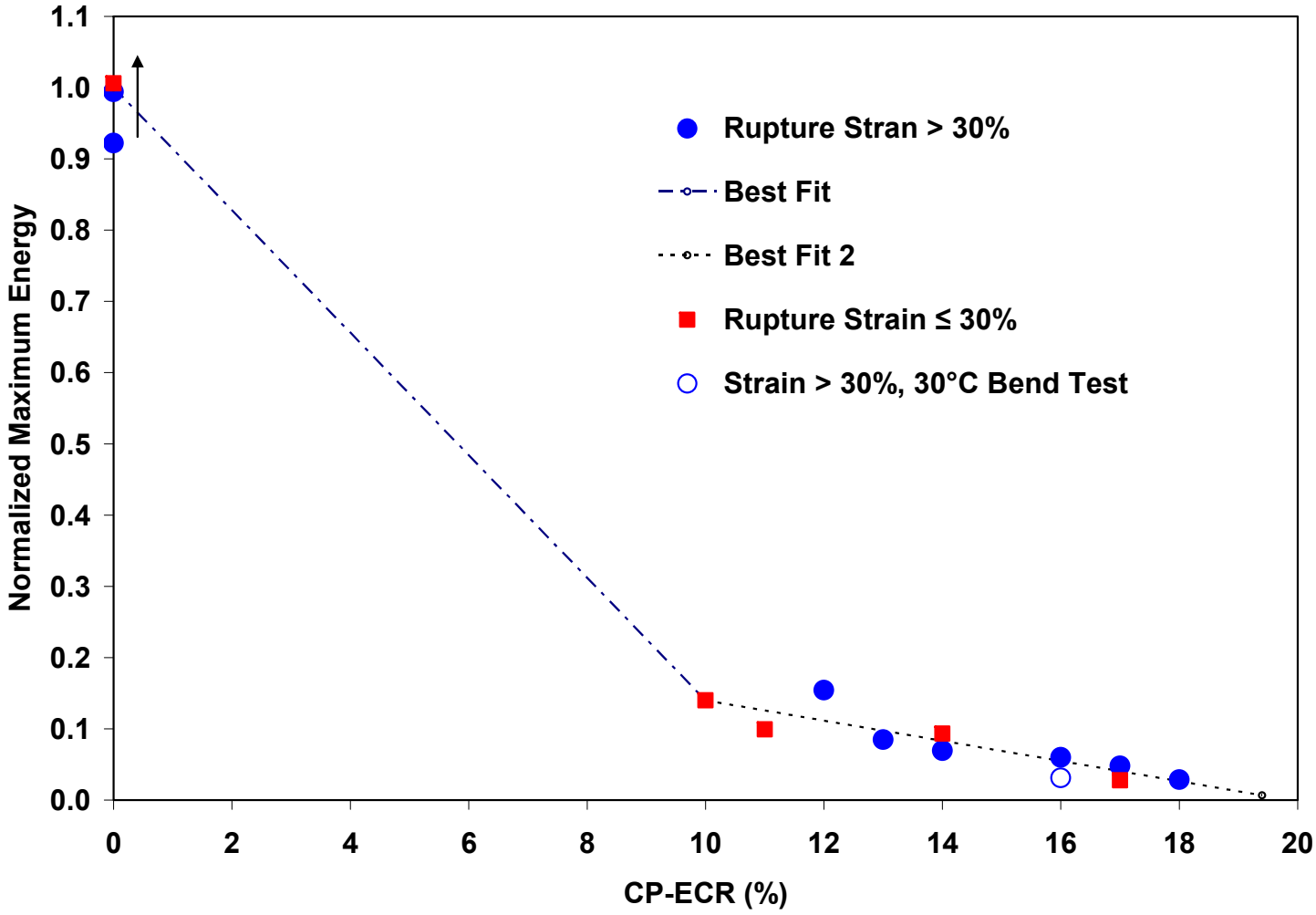

Fig. 3. Normalized maximum energy as a function of oxidation level (CP-ECR) for post-LOCA samples subjected to four-point bending with the rupture region in tension for all tests but one. Bend tests were performed at 135°C and 2 or 1 mm/s to 14-mm maximum displacement. As indicated, one bend test was conducted at 30°C.