Table 1 Summary of Prehydriding Conditions and Results for Zircaloy Segments from which Rodlets were Fabricated for RHT; following prehydriding, segments were annealed for 24-36 hours at 400ºC in flowing argon with some segments subjected to thermal cycling during the anneal to more uniformly distribute the hydrogen. November 7, 2008

Cladding	ANL ID#	Surface Treatment	Gas Phase Hydrogen %	Pre-H T ºC	Pickling Cycles (t, min.)	Thermal Cycles	H-Content from Weight Gain wppm	H-Content (wppm) and Morphology at ≈12 mm from Ends
15×15 Zry-4 (HBR-type)	637A103C	None	100	350	0	1	490	180±3 Uniform hydrides
15×15 Zry-4 (HBR-type)	637A103D4	Al foil	4	350	0	1	580	473±7 Local OD/ID H-rims
15×15 Zry-4 Modern BP	101B2C	Pickling	30	400	1 (2)	2	370	300±60 Local OD/ID H-rims
15×15 Zry-4 Modern BP	101A8	Pickling	30	400	1 (2)	3	290	540±120 Local OD/ID H-rims s
15×15 Zry-4 Modern BP	101B1C	Pickling	30	400	1 (2)	2	400	410±210 No metallography
15×15 Zry-4 Modern BP	101B3	Pickling	30	400	1 (2)	2	555	380±160 Uniform hydrides
15×15 Zry-4 Modern BP	101B4	Pickling	30	400	1 (2)	2	610	440±200 Uniform hydrides
10×10 Zry-2	102B7	Pickling Al Foil	30	400	1 (2)	5	203	68±22 Uniform hydrides
10×10 Zry-2	102B8	Pickling Al Foil	30	400	1 (2)	5	207	48±2 Uniform hydrides
10×10 Zry-2	102B9	Pickling Al Foil	30	400	1 (2)	5	167	50±9 Uniform hydrides

Table 2 Summary of Prehydriding Conditions and Results for ZIRLO Segments from which Rodlets were Fabricated for RHT; following prehydriding, segments were annealed for 24-36 hours at 400ºC in flowing argon with some of the segments subjected to thermal cycling during the anneal to more uniformly distribute the hydrogen. November 7, 2008

Cladding	ANL ID#	Surface Treatment	Gas Phase Hydrogen %	Pre-H T, ºC (Hold time)	Pickling Cycles (t, min.)	Thermal Cycles	H-Content from Weight Gain wppm	H-Content (wppm) and Morphology at ≈12 mm from Ends
17×17 ZIRLO	634B2D	Pickling	30	350 400	3 (6) 2 (4)	3 2	585	400±110 Uniform hydrides
17×17 ZIRLO	634B2F	Pickling	30	400 (60 min.)	1 (2)	2	300	315±10 Uniform hydrides
17×17 ZIRLO	634B4B[a]	Pickling Al Foil	30	400 (60 min.)	1 (2)	1	638	543±204 Uniform hydrides Local OD hydride rims
17×17 ZIRLO	634B4C[a]	Pickling Al Foil	30	400 (60 min.)	1 (3)	1	835	507±155 Uniform hydrides Local OD hydride rims
17×17 ZIRLO	634B4D[a]	Pickling Al Foil	30	400 (60 min.)	1 (2)	1	963	735±140 Hydride rim probable
17×17 ZIRLO	634B4E[a]	Pickling Al Foil	30	400 (60 min.)	1 (2)	1	839	350±70 Hydride rim probable
17×17 ZIRLO	634B4F	Pickling Al Foil	30	400 (60 min.)	1 (2)	5	230	106±11 Uniform hydrides
17×17 ZIRLO	634B4G	Pickling Al Foil	30	400 (60 min.)	1 (2)	5	154	73±38 Uniform Hydrides
17×17 ZIRLO	634B5A	Pickling Al Foil	30	400 (40 min)	1 (2)	5	130	170±85 Uniform Hydrides
17×17 ZIRLO	634B5E	Pickling Al Foil	30	400 (140 min.)	1 (2)	5	524	531±2 Probable OD/ID H-rims

Table 3 Test Matrix for Radial Hydride Treatment of Prehydrided Zircaloy Cladding using Pressurized-and-Sealed Rodlets; HBR = as-fabricated H. B. Robinson type 1970s vintage cladding; BP = belt-polished; TBD = to be determined; November 7, 2008

Cladding	ANL ID#	Hydrogen Content wppm	Hold Time at 400ºC hours	Hoop Stress at 400ºC MPa	Cooling Rate ºC/h	OD Hoop Creep Strain %	RHT-Ring Hydrogen Content wppm	Work Completed
15×15 Zry-4 (HBR-type)	637A103C	227-1460[a]	3	150	20	0.4	260±40 465±90 TBD	Metallography (3) LECO-H (6) Ring Compression (3)
15×15 Zry-4 (HBR-type)	637A103D4	750±80[a]	1	150	5	0.4	530±60 530±20 510±20	Metallography (3) LECO-H (7) Ring Compression (3)
15×15 Zry-4 Modern BP	101B2C	425±110	1	150	5	0.3	400±110 450±110 465±120	Metallography (3) LECO-H (5) Ring Compression (3)
15×15 Zry-4 Modern BP	101A8	1200-2100[a]	0.2 5 cycles 100ºC/cycle	150	5	0.4[d]	970±120 --- 1020±180	Metallography (3) LECO-H (6) Ring Compression (2)
15×15 Zry-4 Modern BP	101B1C	540±130	1	120	5	0.2	570±250 --- 580±310	Metallography (3) LECO-H (6) Ring Compression (2)
15×15 Zry-4 Modern BP	101B3	380[b]	TBD	TBD	5	TBD	---	Segment ready for pressurization/welding
15×15 Zry-4 Modern BP	101B4	440[b]	TBD	TBD	5	TBD	---	Segment ready for pressurization/welding
10×10 Zry-2	102B7	180±70	1	150	5	1.1	130±60 230±60 230±60	Metallography (3) LECO-H (4) Ring Compression (3)
10×10 Zry-2	102B8	207[b]	TBD	TBD	5	TBD	TBD	Segment ready for pressurization/welding
10×10 Zry-2	102B9	167[b]	TBD	TBD	5	TBD	TBD	Segment ready for pressurization/welding

[a]Samples have dense hydride rim on inner-surface from 10-50 µm thick, which was removed after RHT prior to ring compression testing.
[b]Based on sample weight gain; local hydrogen contents for rings are generally higher, especially if inner-surface hydride rim is present

Table 4 Test Matrix for Radial Hydride Treatment of Prehydrided ZIRLO Cladding using Pressurized-and-Sealed Rodlets; TBD = to be determined; November 7, 2008

Cladding	ANL ID#	Hydrogen Content wppm	Hold Time at 400ºC hours	Hoop Stress at 400ºC MPa	Cooling Rate ºC/h	OD Hoop Creep Strain %	RHT-Ring Hydrogen Content wppm	Work Completed
17×17 ZIRLO	634B2D4	620±110	1	≈190	5	1.4	No ID hydride rim observed	Metallography (3) LECO-H (4) Ring Compression (3)
17×17 ZIRLO	634B2F	315±11	1	186	5	---	185±23 171±18 171±18	Metallography (3) LECO-H (4) Ring Compression (3)
17×17 ZIRLO	634B4C3	1000-1400[a]	1	148	5	0.5	645±204 591±172 ≈600±180	Metallography (3) LECO-H (6) Ring Compression (3)
17×17 ZIRLO	634B4E3	600-1700[a]	1	148	5	0.4	≈590±60 589±35 ≈590±60	Metallography (3) LECO-H (4) Ring Compression (3)
17×17 ZIRLO	634B4B3	543±204	1	150	5	0.6	710±190 TBD TBD	Metallography (3) LECO-H (4) Ring Compression (3)
17×17 ZIRLO	634B4D3	738±85	1	150	5	0.5	610±100 690±100 730±100	Metallography (3) LECO-H (7) Ring Compression (3)
17×17 ZIRLO	634B4F3	230[b]	1	TBD	5	TBD	TBD	Segment is ready for pressurization/welding
17×17 ZIRLO	634B4G3	240±90	1	170	5	1.0	240±90	Metallography (3) LECO-H (4) Ring Compression (3)
17×17 ZIRLO	634B5A3	90±10	1	170	5	0.9	90±10	Metallography (3) LECO-H (4) Ring Compression (3)

[a]Samples have dense hydride rim on inner-surface from 10-50 µm thick, which was removed after RHT and prior to ring compression testing.
[b]Based on sample weight gain; local hydrogen contents for rings are generally higher, especially if inner-surface hydride rim is present.

Table 5 Results of Ring Compression (5 mm/s) and Impact (2 m/s) Tests for Radial-Hydride-Treated Zircaloy; HBR = as-fabricated H. B. Robinson type 1970s vintage cladding; BP = modern belt-polished. Unless otherwise indicated, hold temperature at 400ºC and cooling rate were 1 hour and 5ºC/h. November 7, 2008

Cladding Type and RHT Hoop Stress at 400 ºC	Rodlet ID# Ring ID#	Hydrogen Content wppm	Test T ºC	Total Displace. mm	Total Displace. to Crack Initiation mm	Plastic Displace. to Crack Initiation mm	Comment: Ductility Number and Depth of Cracks
15×15 Zry-4	637A103C						
HBR-type	4	260±40	150	1.6	>1.6	>1.1	High ductility
150 MPa	8	465±90	150	1.7	>1.7	>1.1	High ductility
3-h hold	9	≈470±90	RT	≈2	(Impact)	(Impact)	3 cracks
20ºC/h cool							
15×15 Zry-4	637A103D4						
HBR-type	D	530±60	150	2.6	>2.6	>1.9	High ductility
150 MPa	H	530±20	150	1.7	>1.7	>1.1	High ductility
RHT	J	510±20	150	1.7	>1.7	>1.1	High ductility
15×15 Zry-4	101B2C						
Modern BP	4	400±110	150	1.5	>1.5	>0.8	High ductility
150 MPa	8	450±110	RT	≈2	(Impact)	(Impact)	2 cracks
RHT	9	465±120	RT	1.4	>1.4	>0.7	High ductility
15×15 Zry-4	101A8						
Modern BP	D	970±120	150	1.5	0.8	0.1	1 crack; 90%
120 MPa	H	≈1000±150	RT	≈2	(Impact)	(Impact)	4 cracks
RHT	J	1030±180	RT	1.6	≤1.5	≤0.9	2 cracks; 50%
15×15 Zry-4	101B1C						
Modern BP	4	570±250	150	1.6	>1.6	>1.0	High ductility
150 MPa	8	≈580±300	RT	≈2	(Impact)	(Impact)	2 cracks
RHT	9	580±300	RT	1.6	0.9	0.2	2 cracks; ≤80%
10×10 Zry-2	102B7F						
Modern BP	4	130±60	150	1.7	>1.7	>1.3	High ductility
150 MPa	8	230±60	RT	1.7	>1.7	>1.2	High ductility
RHT	9	230±60	150	1.9	>1.9	>1.5	High ductility

Table 6 Results of Ring Compression Tests at 5 mm/s for Radial-Hydride-Treated 17×17 ZIRLO; Rodlet cooled from 400ºC to 200ºC at 5ºC/h; November 7, 2008

RHT Hoop Stress at 400 ºC	Rodlet ID# Ring ID#	Hydrogen Content wppm	Test T ºC	Total Displace. mm	Total Displace. to Crack Initiation mm	Plastic Displace. to Crack Initiation mm	Comment: Ductility; Number and Depth of Cracks
	634B2D4						
≈190 MPa	D	630±110	150	1.6	0.7	0.1	3 cracks; ≤90%
	H	620±110	150	1.6	0.9	0.3	3 cracks; ≤80%
	J	620±110	150	1.6	0.7	0.2	3 cracks; ≤80%
	634B2F						
186 MPa	4	185±23	150	1.6	0.3	0.0	3 cracks; ≤90%
	8	171±18	150	1.6	0.4	0.1	3 cracks; ≤90%
	9	171±18	150	0.6	0.6	0.1	2 cracks; ≤90%
	634B4C3						
148 MPa	D	645±204	150	1.7	>1.7	>1.0	Ductile
	H	591±172	150	1.7	>1.7	>1.0	Ductile
	J	≈600±180	RT	1.6	1.1	0.3	1 crack; 100%
	634B4E3						
148 MPa	D	≈590±50	RT	1.6	1.4	0.6	1 crack; 80%
	H	589±35	150	1.7	>1.7	>1.0	High ductility
	J	594±57	150	1.7	>1.7	>1.0	High ductility
	634B4B3						
150 MPa	D	710±190	150	1.7	>1.7	>1.1	High ductility
	H	<760±250	RT	1.7	1.2	0.5	2 cracks; 90%
	J	<760±250	150	1.7	>1.7	>1.1	High ductility
	634B4D3						
150 MPa	D	610±100	150	1.7	>1.7	>1.1	High ductility
	H	690±100	150	1.7	>1.7	>1.0	High ductility
	J	730±100	150	1.7	>1.7	>1.1	High ductility
	634B4G3						
170 MPa	D	240±90	150	0.6	0.5	0.0	1 crack; 95%
	H	240±90	150	0.7	0.6	0.1	1 crack; 90%
	J	240±90	150	1.6	0.4	0.0	4 cracks; ≤100%
	634B5A3						
170 MPa	D	90±10	150	0.9	<0.9	<0.5	2 cracks; ≤50%
	H	90±10	150	1.6	<1.1	<0.5	2 cracks; ≤90%
	J	90±10	150	1.7	---	---	4 cracks; ≤100%

.