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March 10, 2011

Subject: Weight Gain Data for Zircaloy-4 and ZIRLO Breakaway Tests (Non-Proprietary)

Enclosed is a copy of the non-proprietary report titled "Weight Gain Data for Zircaloy-4 and ZIRLO Breakaway Tests" for information purposes. Westinghouse has been corresponding with the NRC on the subject of breakaway oxidation times for ZIRLO® cladding and differences between values reported by Westinghouse and those reported by Argonne National Laboratory. One remaining question on ZIRLO cladding breakaway oxidation times is the discrepancy between measured weight gains reported by Westinghouse and those calculated using the Cathcart-Pawel relationship. This letter provides data to address this issue.

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Very truly yours,

J. A. Gresham, Manager
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Enclosure

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Weight Gain Data for Zircaloy-4 and ZIRLO® Breakaway Tests (Non-Proprietary)

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Weight Gain Data for Zircaloy-4 and ZIRLO Breakaway Tests

REFERENCES

1. Clifford, P.M., Flanagan, M.E., "Proposed Modification of Cladding Embrittlement Criteria," Paper 2120 Proceedings of Top Fuel 2009, Paris, France, September 6-10, 2009.
2. NUREG/CR-6967, ANL-07/04, Cladding Embrittlement During Postulated Loss-of-Coolant Accidents, M. Billone, Y. Yan, T. Burtseva, R. Daum, July 2008.
3. Letter from J. A. Gresham (Westinghouse) to (NRC),"LTR-NRC-07-52, Westinghouse Breakaway Oxidation Testing Behavior (Non-proprietary)," September 24, 2007.
4. Letter from J. A. Gresham (Westinghouse) to F. Eltawila (NRC),"LTR-NRC-08-29, Updated Westinghouse Breakaway Oxidation Testing Behavior (Non-proprietary)," June 12, 2008.
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6. Letter from J. A. Gresham (Westinghouse) to Michael Lesar (NRC), " LTR-NRC-08-42, Westinghouse Comments on the Technical Basis for New Performance-Based Emergency Core Cooling System Requirements (Non-Proprietary)," September 2, 2008

Executive Summary: This letter provides data to resolve the remaining differences between Westinghouse and Argonne National Laboratory (ANL) on breakaway oxidation times for ZIRLO® cladding. Breakaway oxidation has been raised as a concern for Small Break Loss of Coolant Accidents (SBLOCA) scenarios where temperatures exceed 600 °C for more than 30 minutes. Although the equivalent cladding reacted (ECR) experienced at temperatures < 1,000 °C for these events is small, zirconium alloys experience a breakaway oxidation behavior where, after a certain exposure, the alloy starts to pick up significant hydrogen from the corrosion reaction resulting in loss of post-quench ductility. For this reason breakaway oxidation times have been proposed in Reference 1 as a criteria for the allowable duration of a SBLOCA event.

Westinghouse has been corresponding with the NRC on the subject of breakaway times for ZIRLO cladding and differences between values reported by Westinghouse and those reported by Argonne National Laboratory (ANL) in Reference 2. These communications are covered in References 3 to 6. Based on phone communications with Mike Billone of ANL and Harold Scott (NRC/RES), one remaining question on ZIRLO cladding breakaway times is the discrepancy between measured weight gains reported by Westinghouse and those calculated using the Cathcart-Pawel (C-P) relationship. This letter provides data to address this issue.

Summary of Testing: The data reported here for Zircaloy-4 and ZIRLO cladding were generated in double sided, high temperature steam oxidation tests. All tests were performed using a resistance furnace as the heat source that provided a uniform hot zone of about six to eight inches. This permitted multiple samples (both Zircaloy-4 and ZIRLO) to be exposed during each oxidation run to provide a direct comparison between the alloys. (Appendix 1 identifies the Zircaloy-4 and ZIRLO samples that were included in each oxidation run.) In addition, the positions of the cladding segments were varied in the hot zone of the furnace to cancel out any positional variability.

Samples were introduced to the hot zone by two different techniques as described in Reference 5. One technique produced a fast heating rate (Method A) by dropping the specimens directly into the hot zone of the furnace. The second technique resulted in a reduced heating rate (Method B) as both the specimens and the Alloy 690 tube that served as the steam chamber were inserted into a preheated furnace. Weight gains for samples heated rapidly to temperature (Method A) are tabulated in Table 1 and Table 2 for Zircaloy-4 and ZIRLO, respectively. Table 3 and Table 4 provide measured weight gains for Zircaloy-4 and ZIRLO samples, respectively, that were heated with a reduced heating rate (Method B).

Also included in Table 1 to Table 4 are predicted weight gains that were calculated using the Cathcart-Pawel (C-P) model for high temperature steam oxidation. The integral form of the model is given by:

$$W^2 = 0.362 \int_0^t e^{-20100/T} dt \qquad (1)$$

where
W = weight gain in g/cm^2,
T = temperature in K, and
t = time in seconds.

For constant temperature and minimal heating and cooling times, the C-P equation can be rewritten as

$$W = 0.602\, e^{-10050/T}\, t^{0.5} \qquad (2)$$

Temperature was recorded at time intervals ranging from 2 seconds to 30 seconds. The time-temperature history for each oxidation run permitted the C-P weight gain to be calculated by converting the integral form of the model to the following summation.

$$W = \sqrt{0.362 \sum_i e^{-20100/[0.5(T_{i+1}+T_i)]}(t_{i+1} - t_i)} \qquad (3)$$

While the evaluation of Equation 3 included temperatures less than 1000°C, the contribution of the heat up and cool down to the predicted weight gain was minimal.

A comparison of the predicted and measured weight gains for Zircaloy-4 and ZIRLO samples that were rapidly heated to temperature (Method A) is shown in Figure 1. The plots show good agreement between the predicted and measured weight gains for both alloys. These results validate the temperature measurement during the oxidation runs as measured weight gain is expected to be in agreement with C-P weight gain over this temperature range.

The target temperatures for the samples that were heated with the lower heating rate (Method B) ranged from 950°C to 1020°C. The lower heating rate was used to more closely approximate the temperature transient during a small break loss of coolant accident (SBLOCA). With the exception of heating rate, these oxidation runs were similar to those performed at higher temperature. In particular, the measurement of temperature was identical. A comparison of the predicted and measured weight gains for these samples is shown in Figure 2. The measured weight gains show a significant departure from prediction for both alloys with the deviation being larger for ZIRLO. Since each oxidation run contained both Zircaloy-4 and ZIRLO, the measured weight gains reflect a difference in the oxidation behavior between the alloys. The departure from C-P predictions is likely due to the reduced oxidation temperature and to the reduced heating rate.

Additional high temperature steam oxidation tests were performed over the temperature range of 960°C to 1020°C as reported in Reference 5. These tests were performed as part of the effort to understand the source of the discrepancy between ANL and Westinghouse minimum breakaway oxidation times for ZIRLO. Four of the oxidation runs utilized rapid heating to temperature (Method A) while the remaining six runs used a reduced heating rate (Method C) to reach the target temperature. Details of the thermal history of the specimens are provided in Reference 5. Both measured and predicted weight gains for these tests are provided in Table 5. The data are plotted in Figure 3 and compared to the ZIRLO samples that were slowly heated to temperature using Method B. The samples that were slowly heated to temperature using Method C fall within the scatter of the samples that were heated using Method B. Several of the samples that were rapidly heated to temperature (Method A) show higher measured weight gains due to the onset of breakaway oxidation.

A final set of oxidation runs were performed using a different technique (Method D) to achieve heating rates that were lower than the high heating rates achieved by Method A. Cladding samples were placed inside a ceramic tube to increase the thermal mass of the assembly lowered into the hot zone of the furnace. The increased mass resulted in a reduction in the heating rate. Results from oxidations runs of ZIRLO cladding using Method D are tabulated in Table 6 for target temperatures of 980°C, 1000°C, and 1020°C. The measured and predicted weight gains are plotted in Figure 4 for comparison to the two prior data sets that utilized reduced heating rates (Methods B and C). The good agreement between the three data sets provides added confidence that the results in Figure 2 were not due to the experimental technique that was used to achieve a reduced heating rate.

The large departure between predicted and measured weight gains shown in Figure 2 was assessed in terms of an uncertainty in the measured temperature. Since the predicted weight gains were higher than the measured weight gains, the time-temperature history was adjusted by lowering the measured temperature in order for the C-P weight gain to match the measured weight gain. This assessment was performed for oxidation run LOCA42 with the results summarized in Table 7. The measured time-temperature history resulted in a C-P weight gain of 1490 mg/dm^2 which was significantly higher than the measured weight gains of 1174 mg/dm^2 and 962 mg/dm^2 for Zircaloy-4 and ZIRLO, respectively. In order for the measured and C-P weight gains to be in agreement, temperature would have to be 37°C lower for Zircaloy-4 and 67°C lower for ZIRLO. Such deviations far exceed the uncertainty of the temperature measurement.

To assess the impact of heating rate, oxidation runs were performed at 1000°C using Method A (rapid heat up) for five exposure times ranging from 300 seconds to 2400 seconds. The predicted and measured weight gains for these oxidation runs are given in Table 8 and Table 9 for Zircaloy-4 and ZIRLO, respectively. As before, both alloys were exposed in each oxidation run. The predicted and measured weight gains are plotted in Figure 5 for comparison to oxidation results performed at temperatures ≤ 1020°C using lower heating rates (Methods B, C, and D). The measured weight gains from both Zircaloy-4 and ZIRLO show less deviation from prediction for samples rapidly heated to 1000°C. While the deviation increases with increasing exposure time, the deviation for Zircaloy-4 cladding is less than the deviation for ZIRLO.

A final comparison of the results obtained on samples rapidly heated to 1000°C was made to the ANL results reported in Reference 2. The ANL data are summarized in Table 10 and Table 11 for Zircaloy-4 and ZIRLO, respectively. Samples that exhibited significant breakaway oxidation (i.e., hydrogen levels greater than 500 ppm) were not included in the comparison. The Westinghouse and ANL data are compared in Figure 6. The bulk of the ANL results are for oxidation temperatures in the range of 984°C to 1000°C. As shown in the figure, the Westinghouse results (×) fall within the scatter of the ANL data for samples that are rapidly heated to temperature in the vicinity of 1000°C.

Conclusions

A comparison of the measured and predicted (C-P) weight gains following high temperature steam oxidation over the temperature range of 950°C to 1200°C was performed for both Zircaloy-4 and ZIRLO cladding samples. The following conclusions can be made.

- Measured weight gains from both Zircaloy-4 and ZIRLO samples were in good agreement with Cathcart-Pawel predictions for oxidation temperatures of 1050°C to 1200°C. These samples were heated rapidly to the target oxidation temperature.
- Measured weight gains from both Zircaloy-4 and ZIRLO samples showed significant deviation from Cathcart-Pawel predictions for oxidation temperatures of 950°C to 1020°C. At these lower temperatures, the major experimental difference was the reduced heating rate that was used during the oxidation tests to establish the time for the onset of breakaway oxidation. The lower heating rate was used to more closely approximate the expected heating rate during a SBLOCA.
- Limited high temperature steam oxidation was performed at 1000°C using a rapid heating rate. While the deviation between measured and predicted weight gains increased with increasing oxidation time, the results were within the scatter of the ANL data obtained at oxidation temperatures of 984°C to 1000°C.

Based on test results, ZIRLO cladding has breakaway times of > 5,400 seconds when subjected to temperatures around 1000 °C with heatup rates that are representative of SBLOCA events. The reason for the difference between shorter ANL breakaway times and longer Westinghouse breakaway results was reported in Reference 5. It was determined that heat-up rate is a significant variable for establishing the time to reach breakaway oxidation. The high ramp rates in the ANL tests and lower ramp rates in the Westinghouse test at STD support the observation of shorter times to breakaway oxidation from tests performed at ANL. The fast temperature ramp used with the ANL test setup is much more rapid than the heatup expected for LOCA events where the time at temperatures > 600 °C exceeds 30 minutes. This can be observed by inspecting Figure II-2, Transient Temperature Profiles for a Sample Small Break LOCA in Reference 6, and by inspecting Figure 7 in Reference 5 which compares Westinghouse breakaway heatup times with time temperature profiles from Reference 6 for SBLOCA events.

Table 1 Weight gain results for Zircaloy-4 cladding oxidized at 1050°C using rapid heatup (Method A).

Nominal Temp. (°C)	Nominal Time (sec)	Oxidation Run	C-P Weight Gain (mg/dm^2)	Sample	Measured Weight Gain (mg/dm^2)	$\frac{(\text{Meas.} - \text{CP})}{\text{CP}}$
1050	180	LOCA228	486	K25	481	-0.01
				K26	446	-0.08
	600	LOCA229	793	K27	776	-0.02
				K28	772	-0.03
	1320	LOCA230	1129	K30	1120	-0.01

Table 2 Weight gain results for ZIRLO cladding oxidized at ≥ 1050°C using rapid heatup (Method A).

Nominal Temp. (°C)	Nominal Time (sec)	Oxidation Run	C-P Weight Gain (mg/dm^2)	Sample	Measured Weight Gain (mg/dm^2)	$\frac{(\text{Meas.} - \text{CP})}{\text{CP}}$
1050	180	LOCA228	486	M7	530	0.09
				M8	527	0.08
	296	LOCA241	566	M23	598	0.06
				R7*	608	0.07
				ZL7*	613	0.08
	463	LOCA244	689	M26	694	0.01
				R10*	707	0.03
				ZL10*	708	0.03
	600	LOCA229	793	M10	819	0.03
				M9	817	0.03
	666	LOCA242	817	M24	838	0.03
				R8*	825	0.01
				ZL8*	842	0.03
		LOCA248	857	M29	878	0.02
				R13*	854	0.00
				ZL13*	872	0.02
	907	LOCA246	942	M28	949	0.01
				R12*	939	0.00
				ZL12*	923	-0.02
	1184	LOCA243	1073	M25	1056	-0.02
				R9*	1060	-0.01
				ZL9*	1055	-0.02
	1320	LOCA230	1129	M11	1116	-0.01
				M12	1123	0.00
	1500	LOCA245	1199	M27	1170	-0.02
				R11*	1145	-0.05
				ZL11*	1163	-0.03
1125	131	LOCA234	650	M17	692	0.06
				R1*	685	0.05
				ZL1*	679	0.04
	205	LOCA235	761	M18	799	0.05
				R2*	790	0.04
				ZL2*	808	0.06
	295	LOCA236	862	M19	898	0.04
				R3*	900	0.04
				ZL3*	872	0.01
		LOCA249	829	M30	823	-0.01
				R14*	830	0.00
				ZL14*	811	-0.02
	400	LOCA238	982	M21	1023	0.04
				R5*	985	0.00
				ZL5*	995	0.01
	525	LOCA239	1105	M22	1115	0.01
				R6*	1097	-0.01
				ZL6*	1105	0.00
	660	LOCA237	1224	M20	1228	0.00
				R4*	1230	0.00
				ZL4*	1204	-0.02
1200	142	LOCA250	859	M31	909	0.06
				R15*	925	0.08
				ZL15*	904	0.05

* Samples charged with hydrogen prior to high temperature oxidation.

Table 3 Weight gain results for Zircaloy-4 cladding oxidized at ≤1020°C using slow heatup (Method B).

Nominal Temp. (°C)	Nominal Time (sec)	Oxidation Run	C-P Weight Gain (mg/dm^2)	Sample	Measured Weight Gain (mg/dm^2)	$\frac{(Meas. - CP)}{CP}$
950	5400	LOCA13	1219	11	912	-0.25
				19*	806	-0.34
960	4400	LOCA46	1159	56	711	-0.39
		LOCA51	1156	61*	728	-0.37
	5400	LOCA18	1297	16	818	-0.37
				24*	824	-0.36
970	4400	LOCA45	1212	55	788	-0.35
		LOCA52	1221	62*	838	-0.31
	5400	LOCA15	1500	13	958	-0.36
				21*	979	-0.35
980	4400	LOCA53	1343	63	981	-0.27
		LOCA54	1362	72*	698	-0.49
	5400	LOCA19	1505	17	968	-0.36
				25*	1269	-0.16
990	4400	LOCA44	1433	54	1008	-0.30
		LOCA48	1413	58*	1034	-0.27
	5400	LOCA16	1603	14	1311	-0.18
				22*	1488	-0.07
1000	4400	LOCA42	1490	52	1174	-0.21
		LOCA49	1505	59*	1340	-0.11
	5400	LOCA17	1664	15	1640	-0.01
				23*	1742	0.05
1010	4400	LOCA43	1629	53	1455	-0.11
		LOCA50	1574	60*	1302	-0.17
	5400	LOCA20	1837	18	1884	0.03
				26*	2007	0.09
1020	5400	LOCA21	1756	31	1675	-0.05
				27*	1745	-0.01

* Samples pre-filmed prior to high temperature oxidation.

Table 4 Weight gain results for ZIRLO cladding oxidized at ≤1020°C using slow heatup (Method B).

Nominal Temp. (°C)	Nominal Time (sec)	Oxidation Run	C-P Weight Gain (mg/dm^2)	Sample	Measured Weight Gain (mg/dm^2)	$\frac{(Meas. - CP)}{CP}$
950	5400	LOCA13	1219	11	723	-0.41
				19*	678	-0.44
960	4400	LOCA46	1159	56	639	-0.45
		LOCA51	1156	61*	651	-0.44
	5400	LOCA18	1297	16	698	-0.46
				24*	696	-0.46
970	4400	LOCA45	1212	55	687	-0.43
		LOCA52	1221	62*	703	-0.42
	5400	LOCA15	1500	13	851	-0.43
				21*	866	-0.42
980	4400	LOCA53	1343	63	782	-0.42
		LOCA54	1362	72*	833	-0.39
	5400	LOCA19	1505	17	854	-0.43
				25*	862	-0.43
990	4400	LOCA44	1433	54	890	-0.38
		LOCA48	1413	58*	849	-0.40
	5400	LOCA16	1603	14	942	-0.41
				22*	953	-0.41
1000	4400	LOCA42	1490	52	962	-0.35
		LOCA49	1505	59*	994	-0.34
	5400	LOCA17	1664	15	1096	-0.34
				23*	1044	-0.37
1010	4400	LOCA43	1629	53	1140	-0.30
		LOCA50	1574	60*	1066	-0.32
	5400	LOCA20	1837	18	1279	-0.30
				26*	1271	-0.31
1020	5400	LOCA21	1756	31	1321	-0.25
				27*	1402	-0.20

* Samples pre-filmed prior to high temperature oxidation.

Table 5 Weight gain results for ZIRLO cladding oxidized at ≤1020°C (Reference 5).

Temp. (°C)	Time (sec)	Test (Heating Method)	C-P Weight Gain (mg/dm^2)	Sample	Measured Weight Gain (mg/dm^2)	$\frac{(\text{Meas.} - \text{CP})}{\text{CP}}$
959	4350	LOCA126 (C)	1167	IPS 107 A5	638	-0.45
				STD 4	648	-0.44
				104	659	-0.44
980	3720	LOCA118 (A)	1216	IPS 107 A3	732	-0.40
				STD 2	740	-0.39
				102	771	-0.37
980	4370	LOCA127 (C)	1336	IPS 107 A6	791	-0.41
				STD 5	777	-0.42
				105	815	-0.39
990	4320	LOCA119 (A)	1396	IPS 107 A4	861	-0.38
				STD 3	848	-0.39
				103	890	-0.36
1000	4410	LOCA128 (C)	1549	IPS 107 A7	1000	-0.35
				STD 6	953	-0.38
				106	975	-0.37
1002	4330	LOCA117 (A)	1505	IPS 107 A2	1095	-0.27
				STD 1	1116	-0.26
				101	1022	-0.32
1005	4470	LOCA132 (C)	1618	IPS 107 A11	1142	-0.29
				STD 10	1075	-0.34
				110	1052	-0.35
1010	3830	LOCA129 (C)	1548	IPS 107 A8	1028	-0.34
				STD 7	1005	-0.35
				107	1023	-0.34
1020	4340	LOCA130 (C)	1747	IPS 107 A9	1212	-0.31
				STD 8	1188	-0.32
				108	1320	-0.24
1020	4380	LOCA131 (A)	1690	IPS 107 A10	1509	-0.11
				STD 9	1520	-0.10
				109	1424	-0.16

Table 6 Weight gain results for ZIRLO cladding oxidized at ≤ 1020°C using slow heatup (Method D).

Nominal Temp. (°C)	Nominal Time (sec)	Oxidation Run	C-P Weight Gain (mg/dm^2)	Sample	Measured Weight Gain (mg/dm^2)	$\frac{(Meas. - CP)}{CP}$
980	5000	LOCA271	1440	1ZA2	850	-0.41
				2ZA2	891	-0.38
				3ZA2	894	-0.38
1000	5000	LOCA270	1624	1ZA1	1068	-0.34
				2ZA1	1107	-0.32
				3ZA1	1140	-0.30
1020	5000	LOCA272	1825	1ZA3	1379	-0.24
				2ZA3	1439	-0.21
				3ZA3	1411	-0.23

Table 7 Temperature deviation required in LOCA42 for measured and predicted weight gains to be in agreement.

Nominal Temp. (°C)	Nominal Time (sec)	C-P Weight Gain (mg/dm^2)	Alloy	Sample	Measured Weight Gain (mg/dm^2)	Temp. Adjustment to Achieve Agreement between Meas. and C-P Wt. Gain	
						Temp. Change (°C)	C-P Wt Gain (mg/dm^2)
1000	4400	1490	Zircaloy-4	52	1174	-37	1175
			ZIRLO	52	962	-67	959

Table 8 Weight gain results for Zircaloy-4 cladding oxidized at 1000°C using rapid heatup (Method A).

Nominal Temp. (°C)	Nominal Time (sec)	Oxidation Run	C-P Weight Gain (mg/dm^2)	Sample	Measured Weight Gain (mg/dm^2)	$\frac{(Meas. - CP)}{CP}$
1000	300	LOCA225	387	K19	360	-0.07
				K20	359	-0.07
	720	LOCA231	636	K31	579	-0.09
				K32	559	-0.12
	1200	LOCA226	788	K21	712	-0.10
				K22	723	-0.08
	1800	LOCA232	973	K33	847	-0.13
				K34	858	-0.12
	2400	LOCA227	1116	K23	942	-0.16
				K24	936	-0.16

Table 9 Weight gain results for ZIRLO cladding oxidized at 1000°C using rapid heatup (Method A).

Nominal Temp. (°C)	Nominal Time (sec)	Oxidation Run	C-P Weight Gain (mg/dm^2)	Sample	Measured Weight Gain (mg/dm^2)	$\frac{(Meas. - CP)}{CP}$
1000	300	LOCA225	387	M1	402	0.04
				M2	403	0.04
	720	LOCA231	636	M13	593	-0.07
				M14	609	-0.04
	1200	LOCA226	788	M3	701	-0.11
				M4	700	-0.11
	1800	LOCA232	973	M15	794	-0.18
				M16	797	-0.18
	2400	LOCA227	1116	M5	840	-0.25
				M6	839	-0.25

Table 10 ANL oxidation results from Zircaloy-4 oxidized at 984°C to 1014°C.

Sample	Nominal Temp (°C)	Nominal Time (sec)	C-P Weight Gain (mg/dm²)	Meas. Weight Gain (mg/dm²)	Table No. (Ref. 2)	Comment
-	1000	-	325	390	8	Benchmark
-	1000	-	650	720	8	Benchmark
-	1000	-	975	1100	8	Benchmark
-	1000	-	1105	1250	8	Benchmark
-	1000	-	1300	1460	8	Benchmark
HBRU#93	984	159	245	282	18	-
HBRU#90	984	1500	789	785	18	-
HBRU#84	984	3600	1220	1070	18	-
HBRU#88	984	3800	1250	1070	18	-
HBRU#95	984	3800	1250	1060	18	-
BPZ4#16	986	135	245	285	19	-
BPZ4#15	986	1500	858	807	19	-
BPZ4#10	986	3600	1270	1080	19	-
BPZ4#30	986	4000	1310	1160	20	-
BPZ4#31	986	4500	1390	1280	20	-
BPZ4#18	986	5000	1490	1260	19	-
BPZ4#33	986	5000	1470	1220	20	-
BPZ4#13	986	5400	1550	1210	19	-
BPZ4#34	986	5400	1520	1170	20	-
BPZ4#38	1000	5400	1660	1460	20	-
BPZ4#41	1014	5400	1810	1530	20	-

Table 11 ANL oxidation results from ZIRLO oxidized at 950°C to 1015°C.

ZIRLO Lot	Nominal Temp (°C)	Nominal Time (sec)	C-P Weight Gain (mg/dm^2)	Meas. Weight Gain (mg/dm^2)	Table No. (Ref. 2)	Comment
-	1000	-	325	380	24	Benchmark
-	1000	-	650	680	24	Benchmark
-	1000	-	975	900	24	Benchmark
-	1000	-	1105	1080	24	Benchmark
-	1000	-	1300	1170	24	Benchmark
2006	950	3000	890	680	29	-
2006	970	3000	1020	810	29	-
2006	985	3400	1190	960	29	-
2006	985	3600	1230	1000	29	-
2006	1000	1500	863	868	29	-
2006	1000	3600	1350	1140	29	-
2006	1000	4000	1420	1260	29	-
2006	1015	4000	1560	1510	29	-

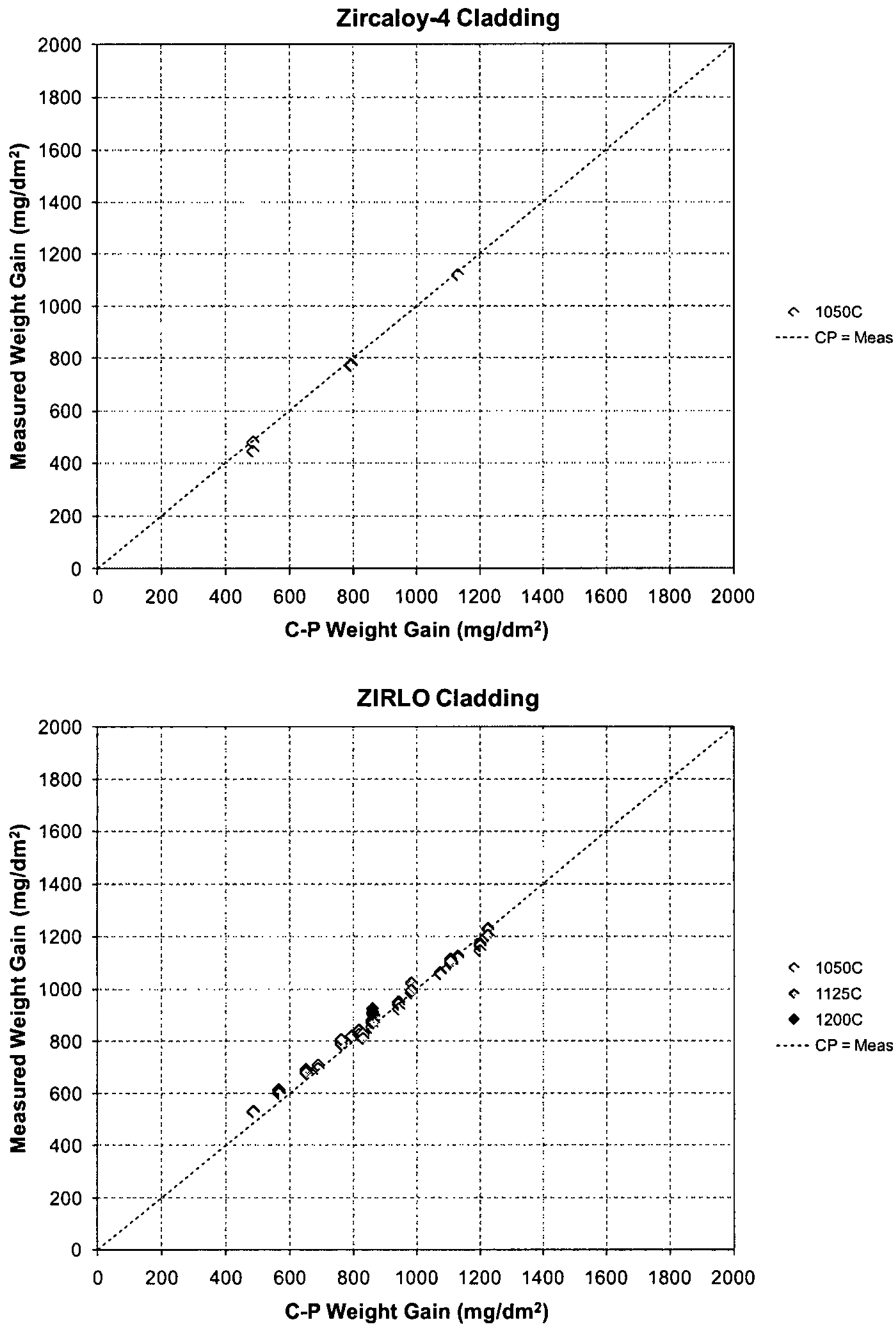
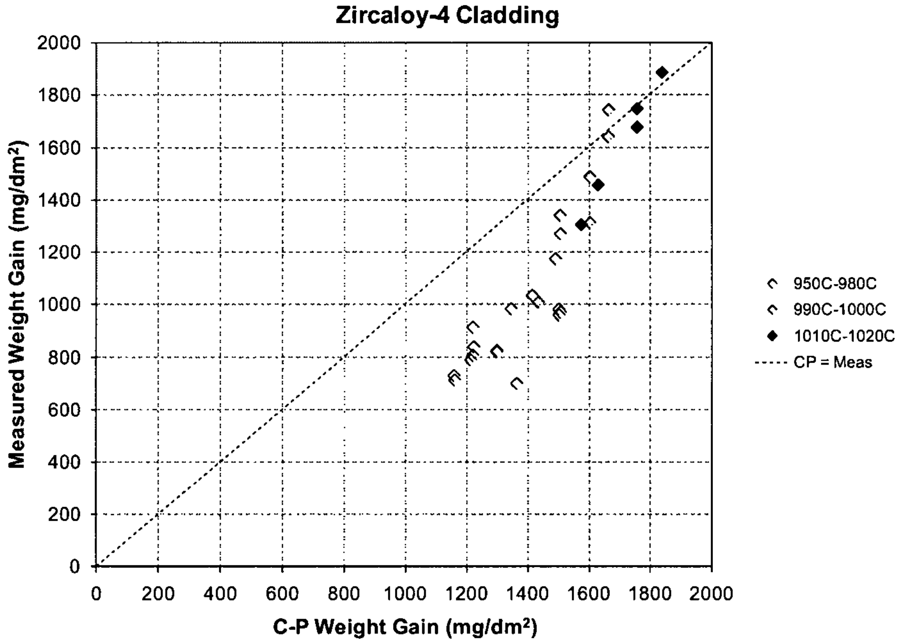


Figure 1 Comparison of predicted (C-P) and measured weight gains for Zircaloy-4 (top) and ZIRLO (bottom) cladding samples oxidized at 1050°C, 1125°C, and 1200°C. All samples were rapidly heated to temperature (Method A).



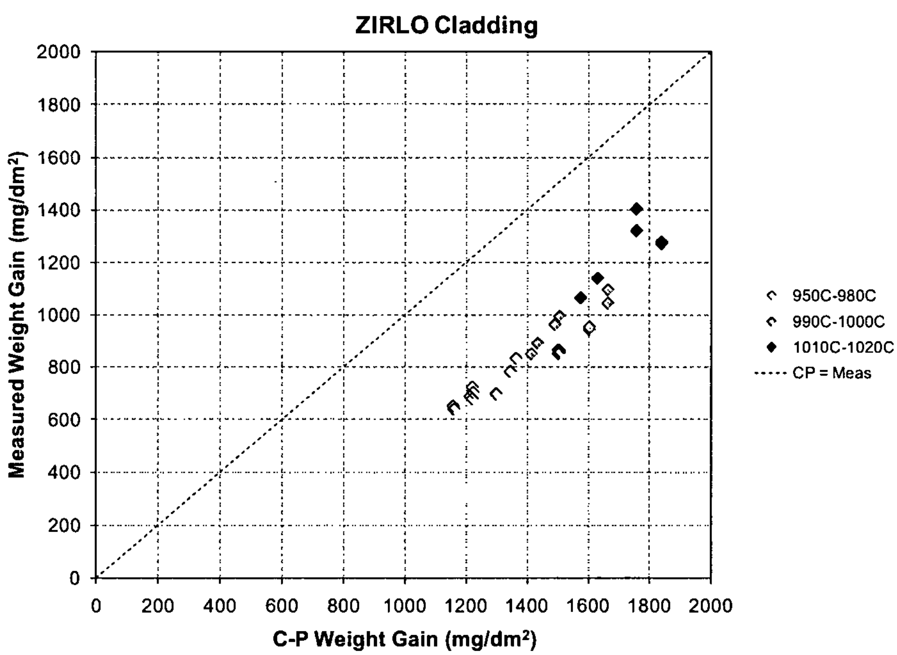


Figure 2 Comparison of predicted (C-P) and measured weight gains for Zircaloy-4 (top) and ZIRLO (bottom) cladding samples oxidized at ≤ 1020°C. All samples were slowly heated to temperature (Method B).

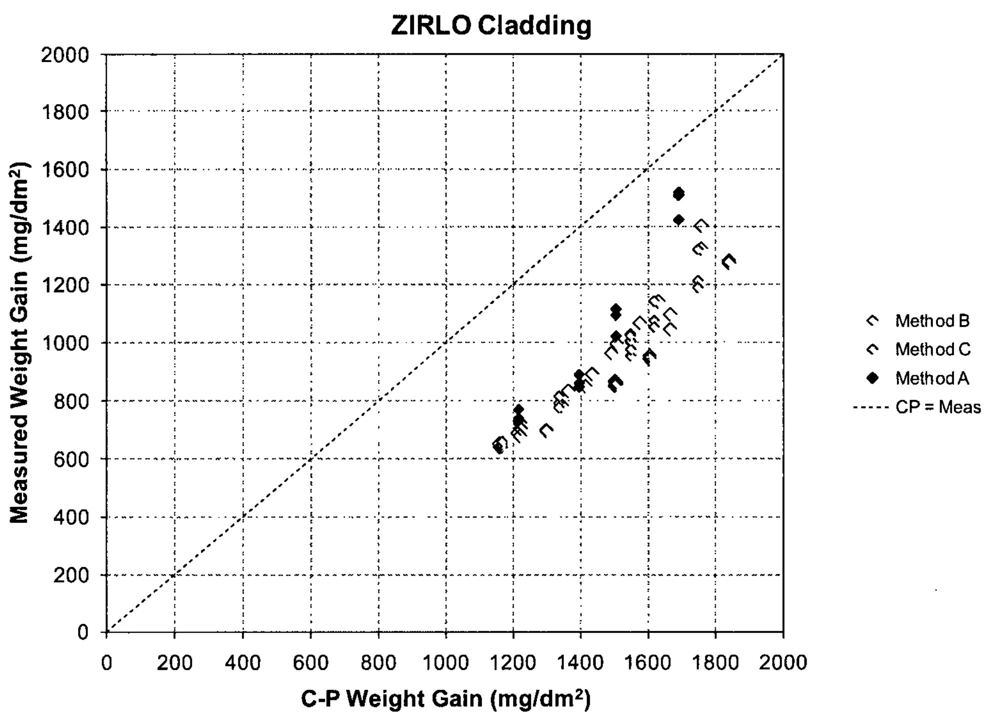


Figure 3 Comparison of predicted (C-P) and measured weight gains for ZIRLO cladding samples oxidized at ≤1020°C using slow heating rates (Methods B and C) and fast heating rate (Method A).

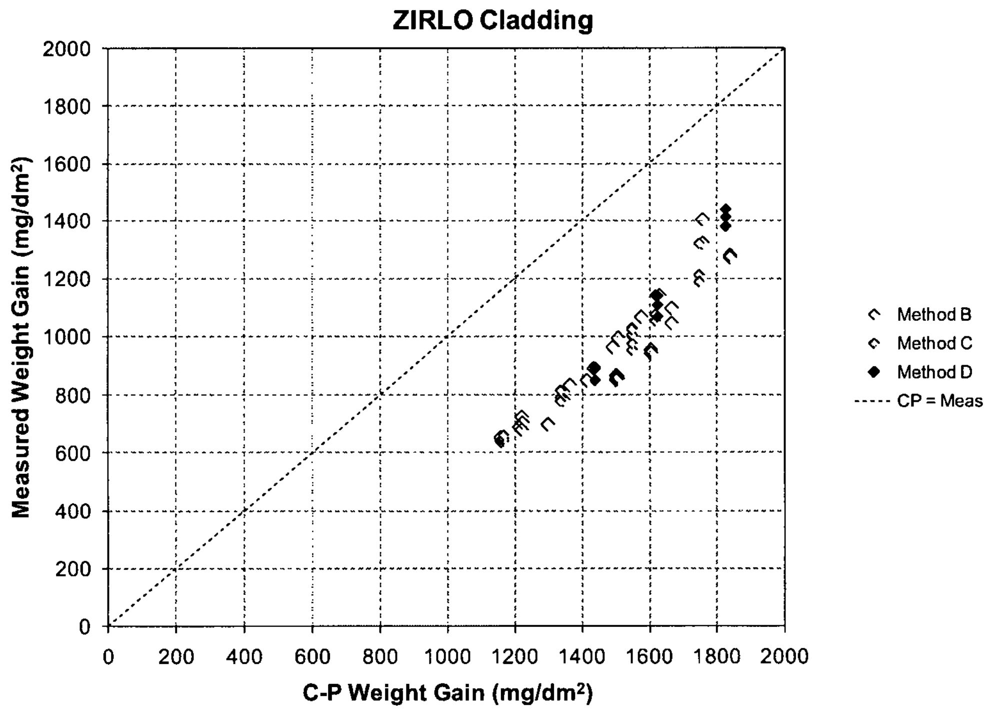
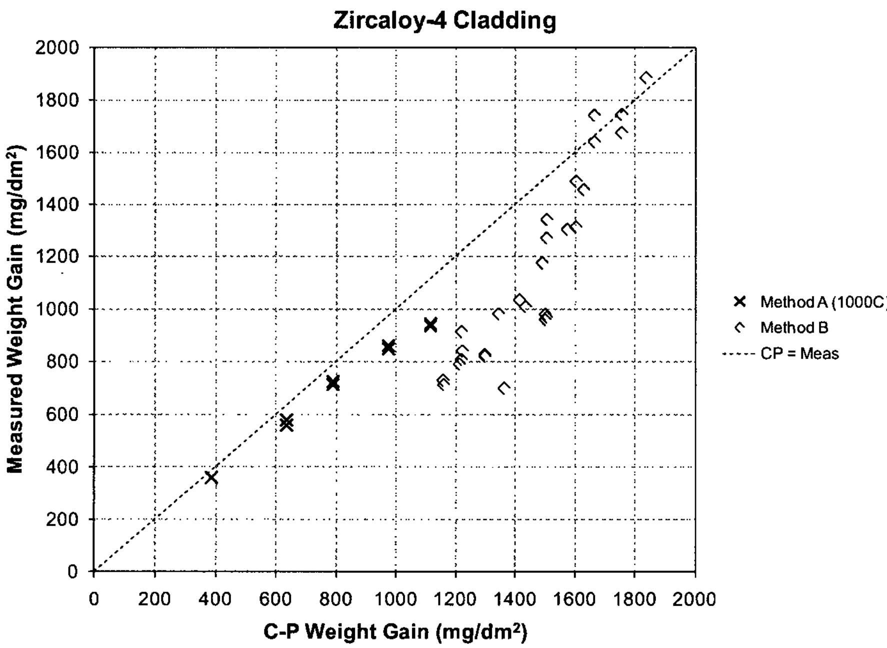


Figure 4 Comparison of predicted (C-P) and measured weight gains for ZIRLO cladding samples oxidized at ≤1020°C using slow heating rates (Methods B, C, and D).



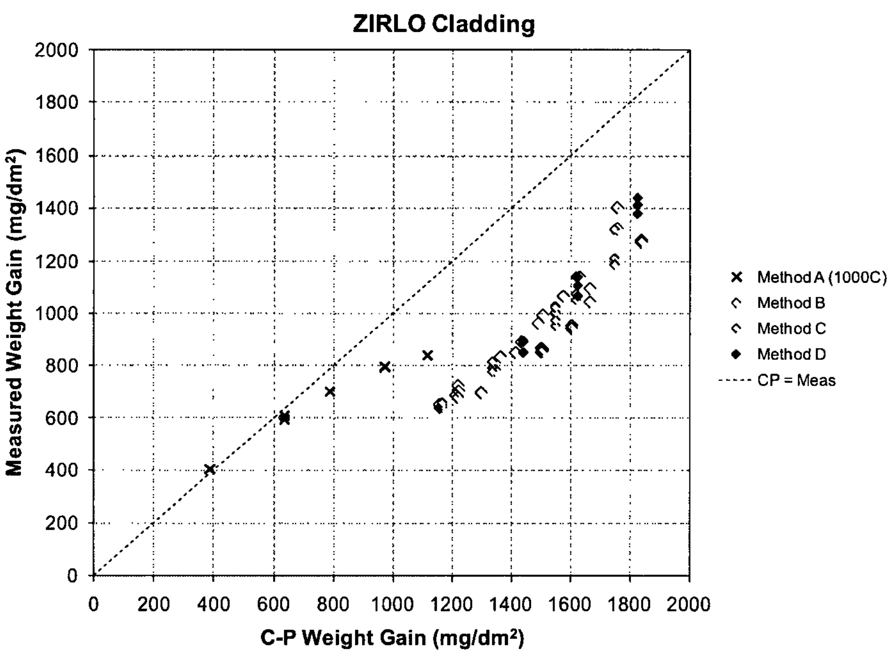
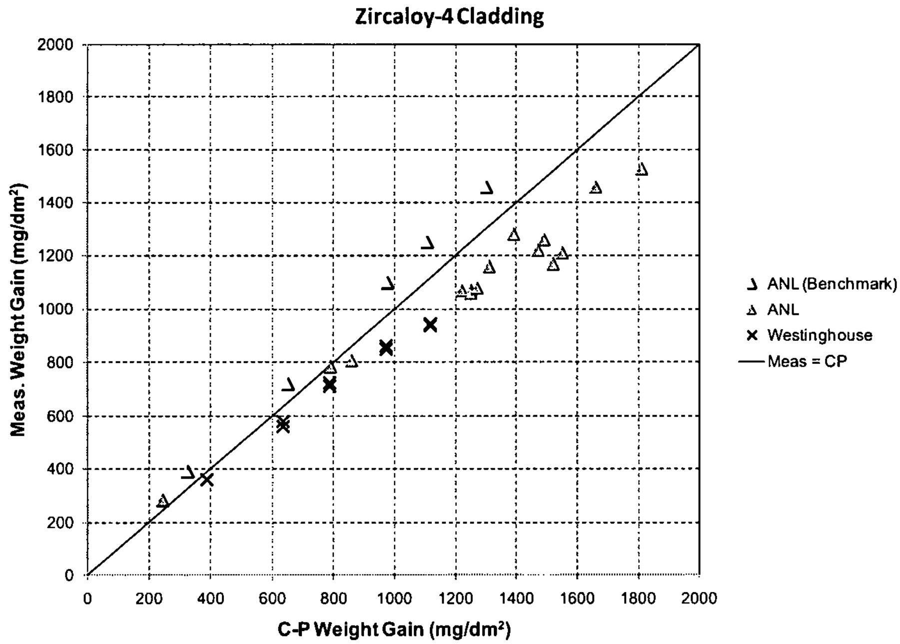


Figure 5 Comparison of predicted (C-P) and measured weight gains for Zircaloy-4 (top) and ZIRLO (bottom) cladding samples oxidized at ≤ 1020°C.



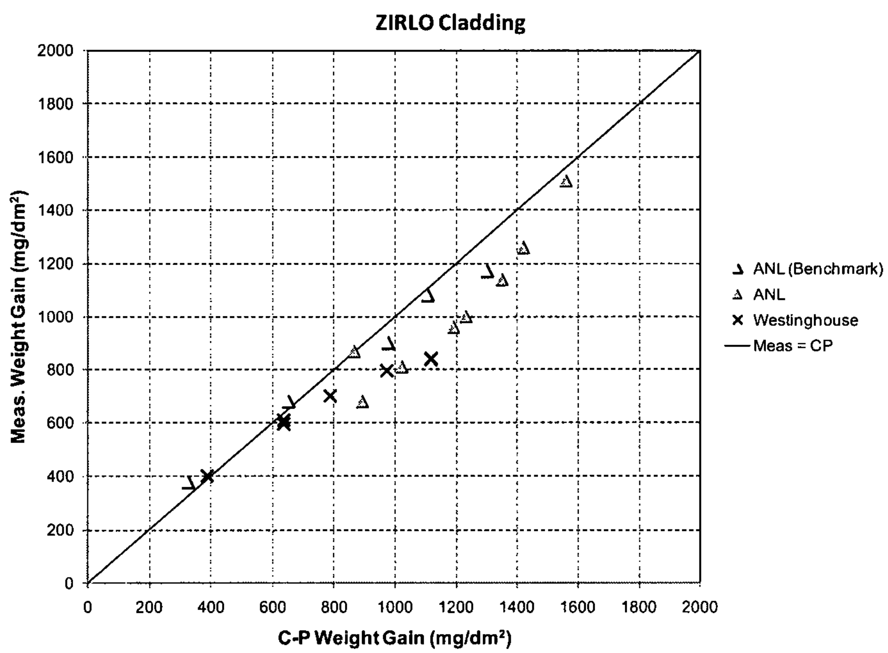


Figure 6 Comparison of predicted (C-P) and measured weight gains for Zircaloy-4 (top) and ZIRLO (bottom) cladding samples oxidized at ≤ 1020°C. All samples were rapidly heated to temperature. ANL samples (triangles); Westinghouse samples (×).

Appendix 1

Oxidation results from Zircaloy-4 and ZIRLO cladding. Data organized by oxidation run.

Note:

- * Samples pre-filmed prior to high temperature oxidation.
- † Samples charged with hydrogen prior to high temperature oxidation.

Appendix 1

Oxidation Run (Method)	Nominal Temp. (°C)	Nominal Time (sec)	C-P Weight Gain (mg/dm^2)	Alloy	Sample	Measured Weight Gain (mg/dm^2)	$\frac{(Meas. - CP)}{CP}$
LOCA13 (B)	950	5400	1219	Zircaloy-4	11	912	-0.25
					19*	806	-0.34
				ZIRLO	11	723	-0.41
					19*	678	-0.44
LOCA15 (B)	970	5400	1500	Zircaloy-4	13	958	-0.36
					21*	979	-0.35
				ZIRLO	13	851	-0.43
					21*	866	-0.42
LOCA16 (B)	990	5400	1603	Zircaloy-4	14	1311	-0.18
					22*	1488	-0.07
				ZIRLO	14	942	-0.41
					22*	953	-0.41
LOCA17 (B)	1000	5400	1664	Zircaloy-4	15	1640	-0.01
					23*	1742	0.05
				ZIRLO	15	1096	-0.34
					23*	1044	-0.37
LOCA18 (B)	960	5400	1297	Zircaloy-4	16	818	-0.37
					24*	824	-0.36
				ZIRLO	16	698	-0.46
					24*	696	-0.46
LOCA19 (B)	980	5400	1505	Zircaloy-4	17	968	-0.36
					25*	1269	-0.16
				ZIRLO	17	854	-0.43
					25*	862	-0.43
LOCA20 (B)	1010	5400	1837	Zircaloy-4	18	1884	0.03
					26*	2007	0.09
				ZIRLO	18	1279	-0.30
					26*	1271	-0.31
LOCA21 (B)	1020	5400	1756	Zircaloy-4	31	1675	-0.05
					27*	1745	-0.01
				ZIRLO	31	1321	-0.25
					27*	1402	-0.20
LOCA42 (B)	1000	4400	1490	Zircaloy-4	52	1174	-0.21
				ZIRLO	52	962	-0.35
LOCA43 (B)	1010	4400	1629	Zircaloy-4	53	1455	-0.11
				ZIRLO	53	1140	-0.30
LOCA44 (B)	990	4400	1433	Zircaloy-4	54	1008	-0.30
				ZIRLO	54	890	-0.38

Appendix 1

Oxidation Run (Method)	Nominal Temp. (°C)	Nominal Time (sec)	C-P Weight Gain (mg/dm²)	Alloy	Sample	Measured Weight Gain (mg/dm²)	$\frac{(Meas. - CP)}{CP}$
LOCA45 (B)	970	4400	1212	Zircaloy-4	55	788	-0.35
				ZIRLO	55	687	-0.43
LOCA46 (B)	960	4400	1159	Zircaloy-4	56	711	-0.39
				ZIRLO	56	639	-0.45
LOCA48 (B)	990	4400	1413	Zircaloy-4	58*	1034	-0.27
				ZIRLO	58*	849	-0.40
LOCA49 (B)	1000	4400	1505	Zircaloy-4	59*	1340	-0.11
				ZIRLO	59*	994	-0.34
LOCA50 (B)	1010	4400	1574	Zircaloy-4	60*	1302	-0.17
				ZIRLO	60*	1066	-0.32
LOCA51 (B)	960	4400	1156	Zircaloy-4	61*	728	-0.37
				ZIRLO	61*	651	-0.44
LOCA52 (B)	970	4400	1221	Zircaloy-4	62*	838	-0.31
				ZIRLO	62*	703	-0.42
LOCA53 (B)	980	4400	1343	Zircaloy-4	63	981	-0.27
				ZIRLO	63	782	-0.42
LOCA54 (B)	980	4400	1362	Zircaloy-4	72*	698	-0.49
				ZIRLO	72*	833	-0.39
LOCA117 (A)	1002	4330	1505	ZIRLO	IPS 107 A2	1095	-0.27
					STD 1	1116	-0.26
					101	1022	-0.32
LOCA118 (A)	980	3720	1216	ZIRLO	IPS 107 A3	732	-0.40
					STD 2	740	-0.39
					102	771	-0.37
LOCA119 (A)	990	4320	1396	ZIRLO	IPS 107 A4	861	-0.38
					STD 3	848	-0.39
					103	890	-0.36
LOCA126 (C)	959	4350	1167	ZIRLO	IPS 107 A5	638	-0.45
					STD 4	648	-0.44
					104	659	-0.44
LOCA127 (C)	980	4370	1336	ZIRLO	IPS 107 A6	791	-0.41
					STD 5	777	-0.42
					105	815	-0.39
LOCA128 (C)	1000	4410	1549	ZIRLO	IPS 107 A7	1000	-0.35
					STD 6	953	-0.38
					106	975	-0.37
LOCA129 (C)	1010	3830	1548	ZIRLO	IPS 107 A8	1028	-0.34
					STD 7	1005	-0.35
					107	1023	-0.34

Appendix 1

Oxidation Run (Method)	Nominal Temp. (°C)	Nominal Time (sec)	C-P Weight Gain (mg/dm^2)	Alloy	Sample	Measured Weight Gain (mg/dm^2)	$\frac{(Meas.-CP)}{CP}$
LOCA130 (C)	1020	4340	1747	ZIRLO	IPS 107 A9	1212	-0.31
					STD 8	1188	-0.32
					108	1320	-0.24
LOCA131 (A)	1020	4380	1690	ZIRLO	IPS 107 A10	1509	-0.11
					STD 9	1520	-0.10
					109	1424	-0.16
LOCA132 (C)	1005	4470	1618	ZIRLO	IPS 107 A11	1142	-0.29
					STD 10	1075	-0.34
					110	1052	-0.35
LOCA225 (A)	1000	300	387	Zircaloy-4	K19	360	-0.07
					K20	359	-0.07
				ZIRLO	M1	402	0.04
					M2	403	0.04
LOCA226 (A)	1000	1200	788	Zircaloy-4	K21	712	-0.10
					K22	723	-0.08
				ZIRLO	M3	701	-0.11
					M4	700	-0.11
LOCA227 (A)	1000	2400	1116	Zircaloy-4	K23	942	-0.16
					K24	936	-0.16
				ZIRLO	M5	840	-0.25
					M6	839	-0.25
LOCA228 (A)	1050	180	486	Zircaloy-4	K25	481	-0.01
					K26	446	-0.08
				ZIRLO	M7	530	0.09
					M8	527	0.08
LOCA229 (A)	1050	600	793	Zircaloy-4	K27	776	-0.02
					K28	772	-0.03
				ZIRLO	M10	819	0.03
					M9	817	0.03
LOCA230 (A)	1050	1320	1129	Zircaloy-4	K30	1120	-0.01
				ZIRLO	M11	1116	-0.01
					M12	1123	0.00
LOCA231 (A)	1000	720	636	Zircaloy-4	K31	579	-0.09
					K32	559	-0.12
				ZIRLO	M13	593	-0.07
					M14	609	-0.04
LOCA232 (A)	1000	1800	973	Zircaloy-4	K33	847	-0.13
					K34	858	-0.12
				ZIRLO	M15	794	-0.18
					M16	797	-0.18

Appendix 1

Oxidation Run (Method)	Nominal Temp. (°C)	Nominal Time (sec)	C-P Weight Gain (mg/dm2)	Alloy	Sample	Measured Weight Gain (mg/dm2)	$\frac{(Meas. - CP)}{CP}$
LOCA234 (A)	1125	131	650	ZIRLO	M17	692	0.06
					R1†	685	0.05
					ZL1†	679	0.04
LOCA235 (A)	1125	205	761	ZIRLO	M18	799	0.05
					R2†	790	0.04
					ZL2†	808	0.06
LOCA236 (A)	1125	295	862	ZIRLO	M19	898	0.04
					R3†	900	0.04
					ZL3†	872	0.01
LOCA237 (A)	1125	660	1224	ZIRLO	M20	1228	0.00
					R4†	1230	0.00
					ZL4†	1204	-0.02
LOCA238 (A)	1125	400	982	ZIRLO	M21	1023	0.04
					R5†	985	0.00
					ZL5†	995	0.01
LOCA239 (A)	1125	525	1105	ZIRLO	M22	1115	0.01
					R6†	1097	-0.01
					ZL6†	1105	0.00
LOCA241 (A)	1050	296	566	ZIRLO	M23	598	0.06
					R7†	608	0.07
					ZL7†	613	0.08
LOCA242 (A)	1050	666	817	ZIRLO	M24	838	0.03
					R8†	825	0.01
					ZL8†	842	0.03
LOCA243 (A)	1050	1184	1073	ZIRLO	M25	1056	-0.02
					R9†	1060	-0.01
					ZL9†	1055	-0.02
LOCA244 (A)	1050	463	689	ZIRLO	M26	694	0.01
					R10†	707	0.03
					ZL10†	708	0.03
LOCA245 (A)	1050	1500	1199	ZIRLO	M27	1170	-0.02
					R11†	1145	-0.05
					ZL11†	1163	-0.03
LOCA246 (A)	1050	907	942	ZIRLO	M28	949	0.01
					R12†	939	0.00
					ZL12†	923	-0.02

Appendix 1

Oxidation Run (Method)	Nominal Temp. (°C)	Nominal Time (sec)	C-P Weight Gain (mg/dm^2)	Alloy	Sample	Measured Weight Gain (mg/dm^2)	$\frac{(Meas. - CP)}{CP}$
LOCA248 (A)	1050	666	857	ZIRLO	M29	878	0.02
					R13†	854	0.00
					ZL13†	872	0.02
LOCA249 (A)	1125	295	829	ZIRLO	M30	823	-0.01
					R14†	830	0.00
					ZL14†	811	-0.02
LOCA250 (A)	1200	142	859	ZIRLO	M31	909	0.06
					R15†	925	0.08
					ZL15†	904	0.05
LOCA270 (D)	1000	5000	1624	ZIRLO	1ZA1	1068	-0.34
					2ZA1	1107	-0.32
					3ZA1	1140	-0.30
LOCA271 (D)	980	5000	1440	ZIRLO	1ZA2	850	-0.41
					2ZA2	891	-0.38
					3ZA2	894	-0.38
LOCA272 (D)	1020	5000	1825	ZIRLO	1ZA3	1379	-0.24
					2ZA3	1439	-0.21
					3ZA3	1411	-0.23