June 09, 2014

MEMORANDUM TO: David Rudland, Chief
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SUBJECT: COOLANT LOOP PIPING FLAW GROWTH ANALYSES

This memorandum provides, in the attachment, results of recent hot and cold leg flaw growth evaluations performed by the NRC staff of the Office of Nuclear Regulatory Research (RES), Division of Engineering (DE), Component Integrity Branch (CIB). The NRC staff conducted a scoping evaluation to determine the leak and rupture characteristics of dissimilar metal butt welds (DMBWs) containing hypothetical pre-existing circumferential flaw at hot leg locations and at cold leg reactor coolant pump (RCP) nozzle locations. In conducting these analyses, the NRC staff assumed that the pre-existing flaws grew due to primary water stress corrosion cracking (PWSCC) and conducted the analyses per ASME Boiler and Pressure Vessel Code, Section XI, IWB-3640, requirements. The staff did not consider fatigue crack growth. The present analysis corrects a minor error in a previous analysis[1] of hot leg DMBWs and extends the analysis to DMBWs in cold leg locations.

The NRC staff chose four representative hot leg cases that span the range of typical leak-before-break approved plants and three RCP suction and discharge nozzle bounding cases from Reference 2 . Table 1 provides the details of the geometry and conditions that were modeled. The NRC staff evaluated the time to leak and time to rupture for stresses resulting from Normal Operating (NO) conditions. For conservatism as the bounding loading case, the NRC staff also evaluated the times to leak and rupture under Safe Shutdown Earthquake (SSE) conditions. Table 2 provides details of the stresses for each of the cases.

The NRC staff performed the evaluations for each of four different weld residual stress (WRS) distributions. Figure 1 illustrates the through-thickness WRS distributions in the axial direction. Two of the cases are from values that the RES staff used for the hot leg geometry in the original Wolf Creek scoping analyses[3]. The first case is for an as-welded Westinghouse-type outlet nozzle with no stainless steel safe end closure weld and no repair. Case 2 is the same geometry and conditions, but with a 15% inside diameter backchip and last pass weld.

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[1] Letter from A. Csontos to T. Lupold dated August 18, 2011, "Hot Leg Evaluation Summary," ADAMS ML112160169

[2] Westinghouse Report: "Flaw Evaluation of CE Design RCP Suction and Discharge, and Safety Injection Nozzle Dissimilar-Metal Welds," Westinghouse Electric Company LLC, Pittsburg, PA, 2009, WCAP-16925-NP, Rev. 1, ADAMS ML092740086

[3] Rudland, D., Shim, D-J., Xu, H., and Wilkowski, G., "Evaluation of Circumferential Indications in Pressurizer Nozzle Dissimilar Metal Welds at the Wolf Creek Power Plant," Summary Report to the NRC, April 2007, ADAMS ML071560398

COOLANT PIPING FLAW GROWTH ANALYSES
by RES/DE

Table 1 Summary of Geometries and Conditions

	Hot Leg	RCP Nozzle
Outside diameter (OD, inches)	33.96	36.00
Wall thickness (t, inches)	2.39	3.00
Temperature (T, °F)	617	547
Pressure (P, psi)	2243	2247
Initial flaw depth (a, inches)	0.634	0.634
Initial flaw length (2c, inches)	2.06	2.06

Table 2 Summary of Stresses for Flaw Evaluation Study

Stress Case	Component	NO		NO + SSE	
		Membrane Stress (ksi)	Bending Stress (ksi)	Membrane Stress (ksi)	Bending Stress (ksi)
A	Hot Leg	6.38	16.68	7.21	18.09
B	Hot Leg	6.41	18.31	9.92	21.35
C	Hot Leg	5.73	2.35	8.61	10.71
D	Hot Leg	6.29	14.27	9.09	26.59
E	RCP Nozzle	5.48	2.41	6.16	17.85
F	RCP Nozzle	5.30	0.92	6.69	15.46
G	RCP Nozzle	5.64	10.34	5.64	19.66

For Case 3, the RES staff developed a WRS profile from the Dominion Engineering, Inc. (DEI) results presented in EPRI report MRP-216[4]. In that report DEI took a 90 degree partial arc deep weld repair and presented the results in the center of the repair, at the end of the repair, and far removed from the repair. The RES staff developed the Case 4 from Case 2 as part of the inlay program[5], but included the effect of a stainless steel safe end weld closure weld.

The NRC staff calculated the PWSCC growth of the assumed initial flaw using the 75th percentile crack growth rates from EPRI MRP-115[6] for the different geometries, stress cases, and WRS cases. The NRC staff calculated the time to leakage and used the net-section collapse criteria and the Alloy 182 Z-factor[7] to calculate time to rupture and the critical crack size for rupture.

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[4] Materials Reliability Program: Advanced FEA Evaluation of Growth of Postulated Circumferential PWSCC Flaws in Pressurizer Nozzle Dissimilar Metal Welds (MRP-216, Rev. 1) EPRI, Palo Alto, CA: 2007. 1015383.MRP-216, Rev. 1

[5] Rudland, D., Brust, F., Zhang, T., Shim, D-J., and Wilkowski G., "Evaluation of The Inlay Process as a Mitigation Strategy for Primary Water Stress Corrosion Cracking in Pressurized Water Reactors," NRC Technical letter report, April 2010, ADAMS ML101260554

[6] Materials Reliability Program: Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182, and 132 Welds (MRP-115) EPRI, Palo Alto, CA: 2004. 1006696. MRP-115

[7] G. Wilkowski, H. Xu, D.-J. Shim, and D. Rudland, "Determination of the Elastic-Plastic Fracture Mechanics Z-factor for Alloy 82/182 Weld Metal Flaws for Use in the ASME Section XI Appendix C Flaw Evaluation Procedures," Proceedings of ASME-PVP2007, paper PVP2007- 26733, July 22-26, 2007

In addition to those assumptions, the staff assumed idealized surface and through-wall flaw shapes. The work in the Advanced Finite Element Analysis (AFEA) project [8] showed this assumption to be typically conservative for the time between leakage and rupture, but reasonably accurate for time to leakage.

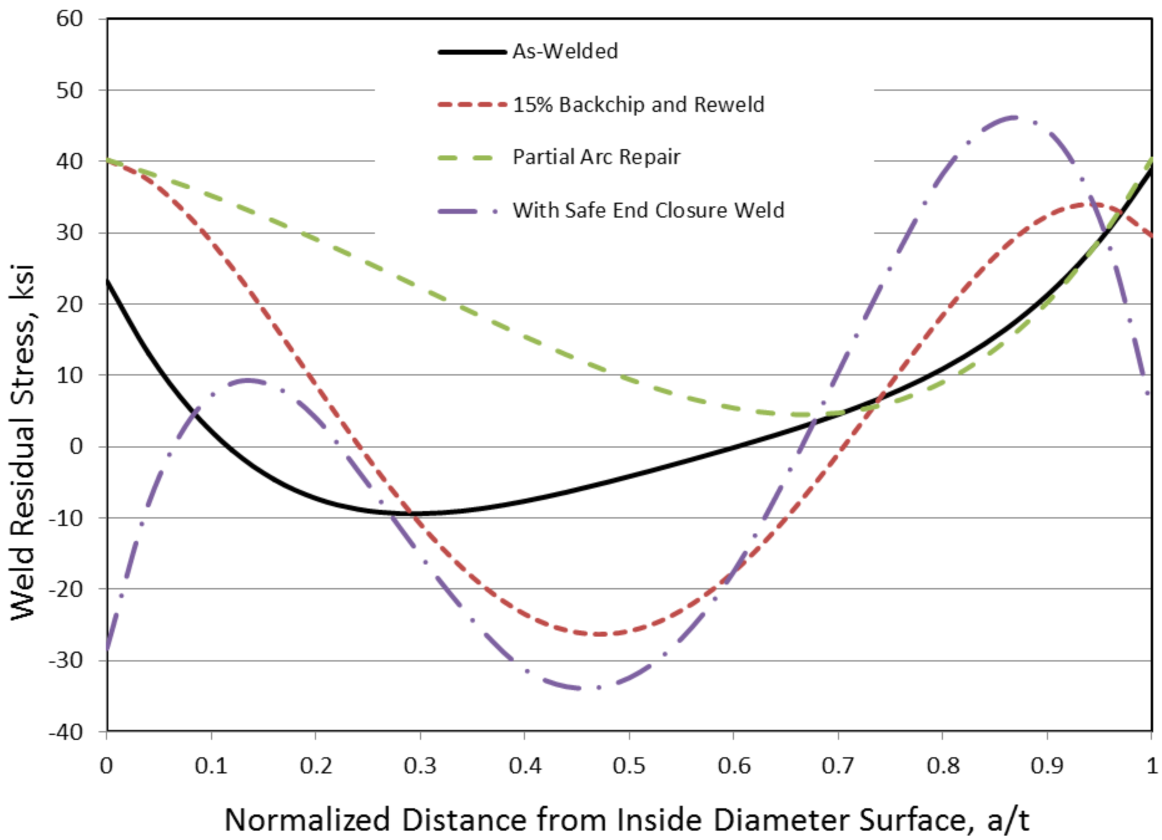

Figure 1 Weld Residual Stress Distributions

The results of these evaluations are shown in Tables 3 and 4. Review of the results provides the following observations:

- The hot leg cases generally had shorter times to leak and rupture than those for the cold leg cases. This is the result of generally higher bending stresses as well as higher hot leg temperatures.
- For all cases where growth of the assumed flaw by PWSCC resulted in leakage in NO conditions, the time between leakage and rupture was over 1 year, providing significant margin to identify the leak and safely shut down the reactor.
- Backchipping the weld root and rewelding decreased the time to leakage and the time between rupture and leakage as compared to the as-welded condition.
- Assuming that the NO+SSE loading could occur for extended time periods, the shortest time to rupture under NO+SSE loading conditions was 1.5 years.

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[8] D. Rudland, D.-J. Shim and A. Csontos, "Natural Flaw Shape Development Due To Stress Corrosion Cracking," PVP2008-61205, Proceedings of ASME-PVP 2008, 2008 ASME Pressure Vessels and Piping Division Conference, July 27-31, 2008, Chicago, IL, USA

- Addition of the residual stress due to the stainless steel safe end closure weld resulted in a significant increase in the time to leakage, sometimes even resulting in crack arrest, but decreased the time between leakage and rupture.
- The time to leakage decreased as the sum of the membrane and bending stress increased, and the time between leakage and rupture generally decreased as the ratio of the bending stress to the sum of the membrane and bending stresses increased.
- The weld residual stresses that resulted from the partial arc repair resulted in the shortest times to leakage and rupture but did not generally result in the shortest times between leakage and rupture.

Table 3 Results of Hot Leg Evaluation for Time to Leak and Time to Rupture

Stress Case	WRS Case	Normal Operation			Normal Operation + Safe Shutdown Earthquake	
		Time to Leak (year)	Time to Rupture (year)	Time between Leak and Rupture (year)	Time to Leak (year)	Time to Rupture (year)
A	As-Welded	2.33	4.33	2.00	2.00	3.75
	15% Backchip	1.83	3.50	1.67	1.58	3.00
	Partial Arc Repair	0.83	3.08	2.25	0.75	2.67
	With Safe-End	7.92	9.42	1.50	5.67	7.08
B	As-Welded	2.08	3.92	1.83	1.50	2.67
	15% Backchip	1.67	3.17	1.50	1.25	2.17
	Partial Arc Repair	0.75	2.83	2.08	0.67	1.83
	With Safe-End	6.25	7.67	1.42	3.08	4.08
C	As-Welded	9.33	17.5	8.17	2.83	5.42
	15% Backchip	5.83	11.5	5.67	2.17	4.25
	Partial Arc Repair	1.33	16.2	14.8	0.92	3.83
	With Safe-End	Arrest	-	-	15.3	17.0
D	As-Welded	2.67	5.08	2.42	1.25	2.17
	15% Backchip	2.08	4.00	1.92	1.08	1.75
	Partial Arc Repair	0.92	3.58	2.67	0.58	1.50
	With Safe-End	12.5	14.2	1.67	2.25	3.08

Table 4 Results of RCP Nozzle Evaluation for Time to Leak and Time to Rupture

Stress Case	WRS Case	Normal Operation			Normal Operation + Safe Shutdown Earthquake	
		Time to Leak (year)	Time to Rupture (year)	Time between Leak and Rupture (year)	Time to Leak (year)	Time to Rupture (year)
E	As-Welded	63.1	106.	42.9	15.2	25.1
	15% Backchip	38.6	63.2	24.6	11.3	19.4
	Partial Arc Repair	9.10	100.	90.9	5.19	16.8
	With Safe-End	Arrest	-	-	47.8	54.9
F	As-Welded	83.8	136.	52.2	16.9	28.2
	15% Backchip	47.8	75.6	27.8	12.4	21.5
	Partial Arc Repair	9.80	165.	155.	5.48	18.9
	With Safe-End	Arrest	-	-	62.6	70.2
G	As-Welded	26.5	45.1	18.6	14.2	23.5
	15% Backchip	18.2	32.8	14.6	10.7	18.2
	Partial Arc Repair	6.71	31.5	24.8	5.04	15.7
	With Safe-End	400.	407.	7.40	41.3	48.0

In order to ensure that the selection of the four hot leg generic descriptions did not invalidate the conclusions, the NRC staff compared the time to leak, time to rupture and time between leak and rupture under NO conditions for 45 plant specific hot leg welds and the 4 different WRS distributions. The calculations assumed an initial flaw depth of 10 percent of the wall thickness and an initial flaw width of twice the depth. These values were chosen in order to approximate the smallest flaw which would have a reasonable probability of detection (POD) in an ASME, Section XI, Appendix VIII qualified ultrasonic (UT) examination for circumferential flaws in reactor pressure vessel nozzles[9]. The results of these evaluations are shown in Figure 2 as the cumulative leak and rupture probabilities with time. The result of this analysis showed that the minimum time to leak was in excess of 1 year and the minimum time to rupture was in excess of 3 years. Also, the minimum time between leak and rupture was in excess of one year, providing significant margin for safe shutdown. The NRC staff notes that the shortest time between leakage and rupture did not correlate well to the shortest time to leakage.

[9] Materials Reliability Program: Development of Probability of Detection Curves for Ultrasonic Examination of Dissimilar Metal Welds (MRP-262, Revision 1) EPRI, Palo Alto, CA: 2009. 1020451 .MRP-262, Rev. 1

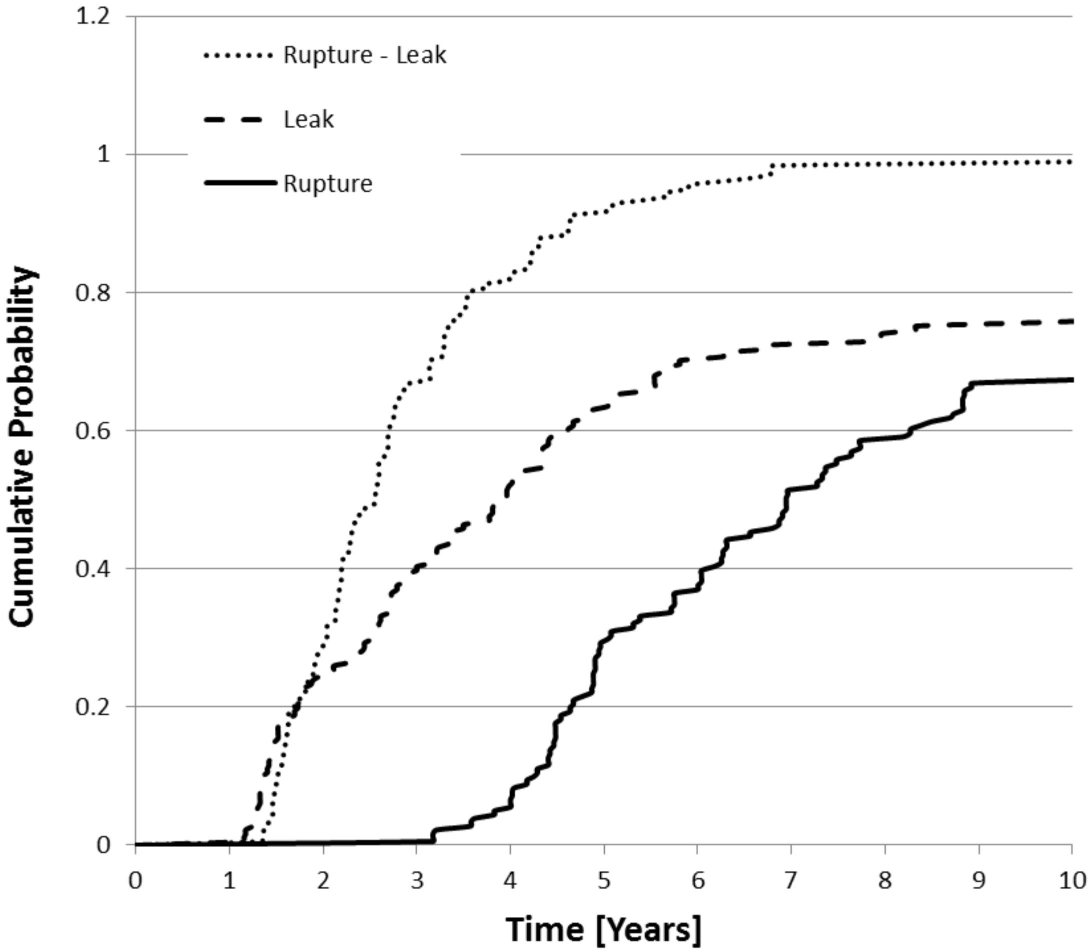

Figure 2. Cumulative probability for time to leak, time to rupture and time between leak and rupture under NO conditions for 45 hot leg welds and 4 WRS conditions

The results of these calculations show that there is significant margin for safe shutdown. While the time to rupture calculations are probably conservative, the level of conservatism is unknown at this point and the NRC staff would have to conduct additional AFEA analyses to quantify the level of conservatism. The NRC staff has further evaluated four of the bounding hot leg cases and has determined that even if a design basis earthquake were to occur immediately prior to leakage, the minimum time before rupture under continuous NO + SSE loading conditions would be 0.5 years, a time period far in excess of the time which SSE could provide loading, and a time duration that would provide significant margin to identify the leak and safely shut down the reactor.

The NRC staff notes that the industry has committed via NEI 03-08 mandatory requirements to having advanced leakage detection systems in place, and compliance with NEI 03-08 mandatory requirements is addressed by INPO review visits and inclusion in Plant corrective action programs. These systems must meet the requirements of WCAP -16423-NP[10] and WCAP-16465-NP[11] and be capable of detecting even small leaks in hours or days, e.g., unidentified 1-day leak rate of 0.3 gallon per minute (gpm) and a 7-day leak rate of 0.1 gpm. These time periods for identifying leakage are significantly shorter than the shortest times between leak and rupture calculated in this study, providing reasonable assurance of structural integrity.

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[10] Westinghouse Report: "Pressurized Water Reactor Owners Group Standard Process and Methods for Calculating RCS Leak Rate for Pressurized Water Reactors," Westinghouse Electric Company LLC, Pittsburg, PA, 2006, WCAP-16423-NP, Rev. 0, ADAMS ML070310084

[11] Westinghouse Report: "Pressurized Water Reactor Owners Group Standard Process and Methods for Calculating RCS Leak Rate for Pressurized Water Reactors," Westinghouse Electric Company LLC, Pittsburg, PA, 2006, WCAP-16465-NP, Rev. 0, ADAMS ML070310082

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[12] Westinghouse Report: “Pressurized Water Reactor Owners Group Standard Process and Methods for Calculating RCS Leak Rate for Pressurized Water Reactors,” Westinghouse Electric Company LLC, Pittsburg, PA, 2006, WCAP-16423-NP, Rev. 0, ADAMS ML070310084

[13] Westinghouse Report: “Pressurized Water Reactor Owners Group Standard Process and Methods for Calculating RCS Leak Rate for Pressurized Water Reactors,” Westinghouse Electric Company LLC, Pittsburg, PA, 2006, WCAP-16465-NP, Rev. 0, ADAMS ML070310082