August 18, 2011

MEMORANDUM TO: Timothy R. Lupold, Chief
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Division of Component Integrity
Office of Nuclear Reactor Regulation

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SUBJECT: HOT LEG FLAW EVALUATION SUMMARY

This memo contains the non-proprietary version of a recent hot leg flaw evaluation and sensitivity analyses. Staff from the Office of Nuclear Regulatory Research (RES), Division of Engineering (DE), Component Integrity Branch conducted a scoping flaw evaluation analyses to determine the leak and rupture characteristics of an indication in a dissimilar metal weld at a hot leg reactor nozzle location.

In conducting these analyses, RES staff assumed primary water stress corrosion cracking (PWSCC) and conducted the analyses per ASME IWB-3640 requirements. The staff did not consider fatigue initiation and crack growth. Below are the inputs and assumptions for these analyses:

- Outside pipe diameter, D_o= 34.1 inch
- Wall thickness, t = 2.62 inch
- Initial flaw depth, a_o= 0.634 inch
- Initial flaw length, $2c_o$= 2.06 inch – as measured on ID
- Flaw length-to-depth ratio, c/a= 1.62
- Flaw depth-to-thickness ratio, a/t= 0.24
- Flaw depth-to-length ratio, a/2c= 0.31
- Pipe internal pressure, P= 2250 psi
- Pipe Temperature, T = 611 F

Table 1 Loads for flaw evaluation study

Load Case	Normal operating (NO) axial load, lbs	NO bending load, ft-kips	NO+Safe shut down (SSE) axial load, lbs	NO+SSE bending load, ft-kips
A	1,482,000	2,393.8	1,674,000	2,595.5
B	1,507,000	2,648.3	2,332,000	3,087.1
C	1,386,000	348.3	2,083,000	1,586.0
D	1,495,000	2,088.1	2,161,000	3,889.5

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The loads chosen for this evaluation span the range of typical leak-before-break approved plants. RES staff in consultation with Office of Nuclear Reactor Regulation staff chose four cases and Table 1 provides the details.

The staff made several assumptions on welding residual stress (WRS). Figure 1 illustrates the assumed through-thickness stress distributions. The first two curves are the values that the staff used in the original Wolf Creek scoping analyses[1] when considering a hot leg geometry. The first case is a Westinghouse-type outlet nozzle with no stainless steel safe end weld. The second is the same geometry, but with a 15% backchip and last pass weld. The third curve is for a limited extent deep weld repair. RES staff developed this curve from the Dominion Engineering, Inc. (DEI) results presented in MRP-216[2]. In that report, DEI took a 90 degree weld repair and presented the results in the center of the repair, at the end of the repair, and far removed from the repair. Using those trends, the staff developed the WRS shown in Figure 1. The fourth curve is identical to curve 2, but includes the stainless steel safe end weld. The staff generated this case in the inlay program[3].

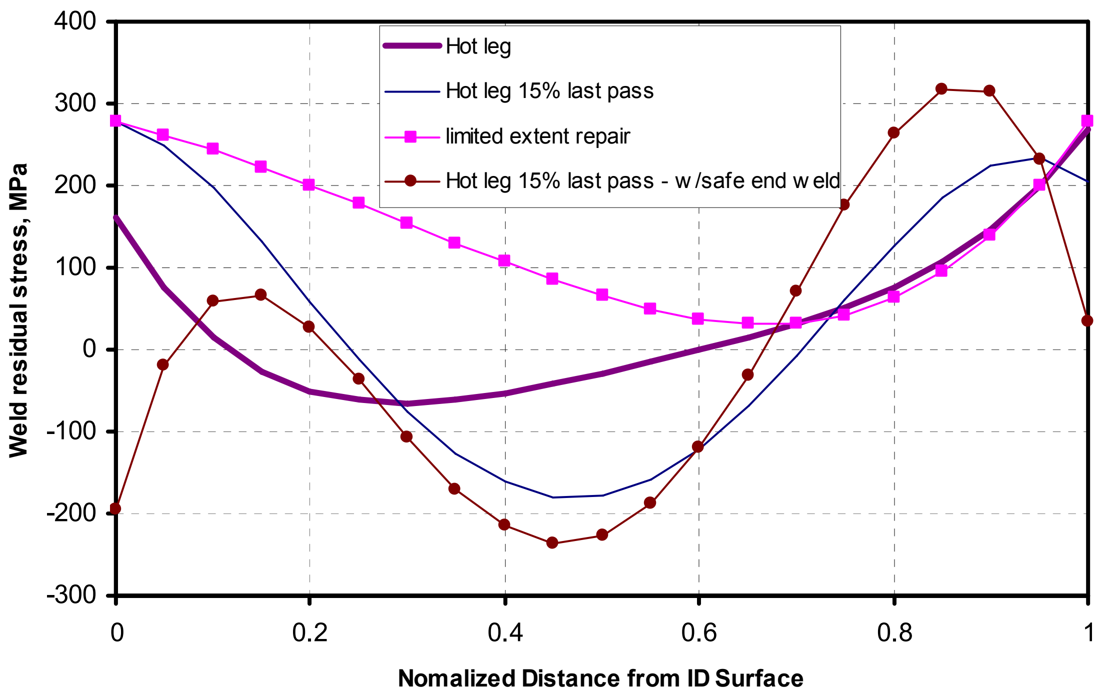

Figure 1 WRS assumptions (no safe end weld)

The staff calculated the PWSCC growth using these residual stress fields, the operating loads, the geometry, and the MRP-115[4] crack growth rates (75th percentile). The staff used the net-

[1] 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 (ML071560398).
[2] 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.
[3] 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, ML101260554, April 2010
[4] Materials Reliability Program (MRP) 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.

section collapse criteria and the Alloy 182 Z-factor[5] to calculate the critical crack size. In addition to those assumptions, the staff assumed idealized flaw shapes (surface and through-wall). From the work in the Advanced Finite Element Analysis (AFEA) project, this assumption is typically conservative for the time between leakage and rupture, but is reasonably accurate for time to leakage[6].

Figure 4 provides an example of the results. In this figure, the pink line is the through thickness crack behavior, the blue line is the crack length behavior, and the red lines are the through-wall crack critical crack size for both NO and NO+SSE. Note the step in the crack length at leakage. This step is due to the assumption that the resulting idealized through-wall crack at leakage has the same crack area as the surface crack.

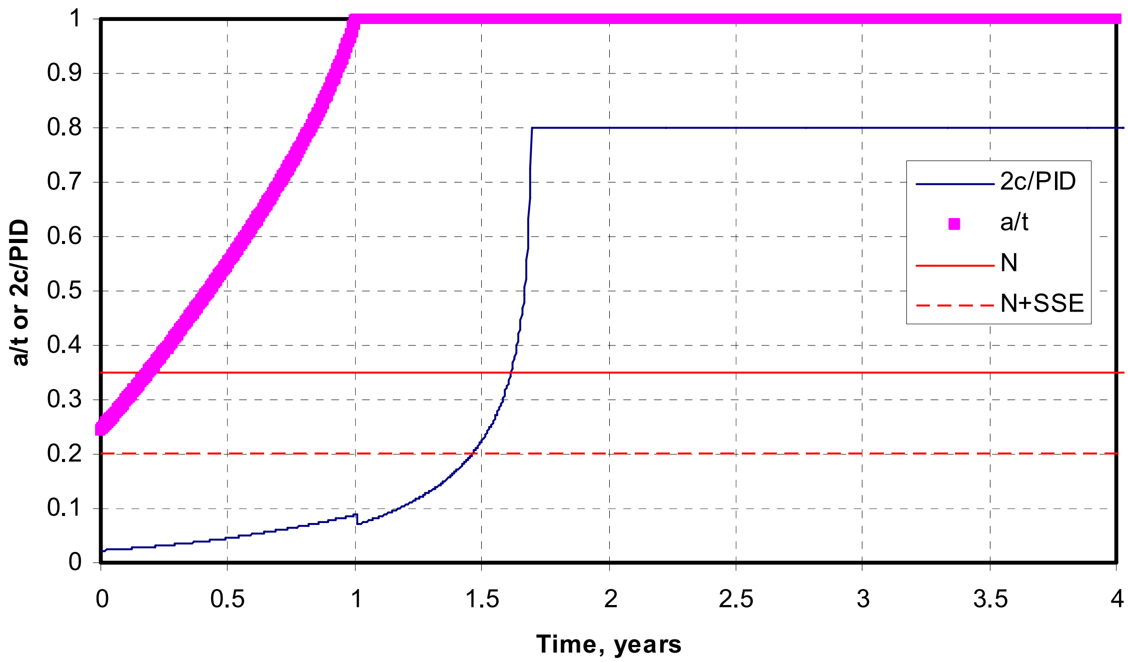

Figure 2 Flaw growth for limited extent ID weld repair – Case D

Table 2 summarizes the time to leakage and rupture The limiting (time between leakage and rupture) case is Case 15 and illustrates that the time to leakage is 1.01 years, and the time between leakage and rupture is 0.47 years.

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[5] 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-PVP 2007, paper PVP2007- 26733, July 22-26, 2007.

[6] 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.

Table 2 Summary of times to leakage and rupture

Case	Load Case	Bending Stress N ksi	Bending Stress N+SSE ksi	WRS	Time (years) Leakage	Time (years) Rupture N	Time (years) Rupture N+SSE	Time between leak and rupture (years) N	Time between leak and rupture (years) N+SSE
1	A	15.15	16.43	Hot Leg with no repair, 15% backchip, no safe end	2.59	4.00	3.98	1.41	1.40
2	A	15.15	16.43	Hot Leg with no repair, no backchip, no safe end	3.41	5.23	5.20	1.82	1.79
3	A	15.15	16.43	Hot leg with 135 deg repair, no safe end	1.05	1.63	1.61	0.58	0.57
4	A	15.15	16.43	Hot Leg with no repair, 15% backchip, with safe end	17.83	18.94	18.59	1.12	0.77
5	B	18.36	21.40	Hot Leg with no repair, 15% backchip, no safe end	1.70	3.03	2.83	1.33	1.13
6	B	18.36	21.40	Hot Leg with no repair, no backchip, no safe end	2.17	3.82	3.65	1.65	1.48
7	B	18.36	21.40	Hot leg with 135 deg repair, no safe end	0.76	1.36	1.29	0.60	0.53
8	B	18.36	21.40	Hot Leg with no repair, 15% backchip, with safe end	6.90	8.13	7.97	1.23	1.07
9	C	2.26	10.30	Hot Leg with no repair, 15% backchip, no safe end	5.93	11.27	10.06	5.35	4.14
10	C	2.26	10.30	Hot Leg with no repair, no backchip, no safe end	9.62	18.17	17.20	8.55	7.58
11	C	2.26	10.30	Hot leg with 135 deg repair, no safe end	1.36	2.89	2.74	1.53	1.39
12	C	2.26	10.30	Hot Leg with no repair, 15% backchip, with safe end	arrest	N/A	N/A	N/A	N/A
13	D	14.24	26.53	Hot Leg with no repair, 15% backchip, no safe end	2.51	4.04	3.58	1.53	1.06
14	D	14.24	26.53	Hot Leg with no repair, no backchip, no safe end	3.31	5.23	4.81	1.92	1.50
15	D	14.24	26.53	Hot leg with 135 deg repair, no safe end	1.01	1.62	1.48	0.61	0.47
16	D	14.24	26.53	Hot Leg with no repair, 15% backchip, with safe end	17.46	18.67	18.33	1.21	0.87

Table 2 provides the following observations:

- The case with the lowest bending stress (Load Case C) did not produce significantly long surface cracks. This case produced the longest flaw length at leakage (~20% of circumference), but the critical crack sizes were large due to the low bending stress.
- The case with the shortest time to rupture was the high SSE loading of Load Case D.
- With the safe end included in the analyses, the case with the shortest time to rupture (Load Case B) had leakage in about 7 years and 1.07 years between leakage and rupture.

From these results, there is sufficient time between leakage and rupture for the initial flaw size assumed. Please note that the normal operating bending loads are not that different between Load Case A and Load Case B (15.15 ksi versus 18.36 ksi). This 20% increase in loads decreased the time to leakage by a factor of 2.5.

Concluding points about this sensitivity analysis:

- As expected, the effects of the safe end weld decreased the time to leakage considerably; however, the initial crack size was very close to a 135 degree weld repair. The safe end would have some impact on these high residual stresses, but not to the effect shown here. Currently, RES does not have a residual stress case with a partial arc repair and a safe end weld.
- The “time to rupture” calculations are probably conservative, but the level of conservatism is unknown at this point. The staff would have to conduct additional AFEA analyses to quantify this conservatism.
- From a fleet wide standpoint, a flaw with this initial size is not a safety concern since the MRP-139 program assures the hot leg mitigation/inspection occur before this size crack would become critical. In the worst case, leakage would occur in 0.76 years, with an additional 0.56 years between leakage and rupture. Per MRP-139, the industry mitigated/inspected the large diameter hot legs by the end of 2009. The probabilities are reasonably low that a hot leg without a safe end weld and high bending loads will have this size circumferential flaw present near a long partial arc repair. Even if one exists and it does leak, sufficient time exists to repair it before it becomes critical.

Table 3 Summary of times to leakage and rupture

		Bending Stress			Time (years)			Time between leak and rupture	
		N	N+SSE			Rupture		(years)	
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