Assessment of the thermal aging embrittlement effect on RCS pipings of Kori 3, 4 NPPs

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1. Introduction

CASS(cast austenitic stainless steel) material has intrinsic possibility to be embrittled by thermal aging due to its duplex phase structure under operating conditions of light-water reactors. The degradation mechanism of thermal aging embrittlement is known to be primarily attributed to the formation of Cr-rich α' phase by spinodal decomposition of ferrite phase during service at 280-330°C. UNNRC proposed the screening criteria to determine the susceptibility of CASS components to thermal aging embrittlement through the letter dated on May 19, 2000[1] after the intensive reviews of the works of ANL[2] and the report of EPRI[3] and fixed them as the regulatory positions for the license issue concerning thermal aging embrittlement of CASS materials in its regulatory document, GALL Report[4]. As a part of the Periodic Safety Review of Kori 3&4 NPPs, the susceptibility to thermal aging embrittlement of Kori 3&4 RCS primary pipings constructed from the CASS material with ASME spec. SA351 Grade CF8A was estimated using the methods and procedures obtained as the results of ANL's research on CASS[2,5] .

2. Methods and Results

GALL report provides two methods to estimate the susceptibility of CASS component to thermal aging embrittlement. One is to determine with molybdenum(Mo) content, casting method, and ferrite content calculated by using the Hull's equivalent factors; for low-Mo content (0.5 wt.% max) steels, only static-cast steels with >20% ferrite are potentially susceptible and for high-Mo (2.0 to 3.0 wt.%) steels, static-cast steels with > 14% ferrite and centrifugal-cast steels with > 20% ferrite are potentially susceptible to thermal embrittlement. The other method is to differentiate between CASS materials that are nonsusceptible and potentially susceptible to thermal aging embrittlement with the value of saturated fracture toughness of CASS material at a crack depth of 2.5 mm; a fracture toughness value of 255kJ/m^2 is the threshold in this method

2.1. Ferrite Content Method

Based on the data from CMTRs (Certified Material Test Records) of Kori 3&4 RCS primary piping, chemical compositions were reviewed and ferrite contents were calculated using Hull's equivalent factors. Neither centrifugally casted straight-pipings nor static-casted elbows contain molybdenum content so that the screening criterion in the case of low-molybdeum content(0.5 wt.% max.) steels are applied to Kori 3&4 RCS primary piping; only static-cast steels with above 20% ferrite are potentially susceptible to thermal aging embrittlement .

For each heat, delta-ferrite content was calculated by

$$\delta_c = 100.3(Cr_{eq}/Ni_{eq})^2 - 172.72(Cr_{eq}/Ni_{eq}) + 74.22 \quad (1)$$

where Cr equivalent factor and Ni equivalent factor are respectively expressed as

$$Cr_{eq} = Cr + 1.21(Mo) + 0.48(Si) - 4.99 \quad (2)$$

$$Ni_{eq} = (Ni) + 0.11(Mn) - 0.0086(Mn)^2 + 18.4(N) + 24.5(C) + 2.77 \quad (3)$$

As the concentrations of N were not available in CMTRs, the recommended value of 0.04wt.% by NUREG/CR-4513[2] was used in calculating the value of Ni equilibrium factor for each heat. Table 1 shows the chemical composition and the calculated ferrite content for each static cast elbow. The values of ferrite content are all under 20% and the maximum value is 15.89% ferrite in the loop 2 crossover-leg, which is far from the screen criterion. In additional work on centrifugal cast strainght-pipings, the values of percent ferrite were evaluated to be approximately in the range of 9.7-14.3 % ferrite. Thus the Kori 3&4 RCS primary pipings manufactured form CASS are not susceptible to thermal aging embrittlement and will continue to maintain their metallurgical integrities.

Table 1. Calculation results of ferrite content in Kori 3&4 static-cast elbows.

Piping	C	Ni	Mn	P	Si	S	Cr	Mo	Co	Ferrite
L2 HL Elbow	0.02	8.48	0.68	0.029	1.13	0.01	19.64	-	0.09	14.56
L3 HL Elbow	0.07	9.08	0.68	0.032	1.12	0.013	19.93	-	0.1	6.69
L2 CL Elbow	0.05	8.91	0.98	0.028	1.2	0.013	20.89	-	0.08	13.72
L1 XL Elbow1	0.07	9.08	0.68	0.032	1.12	0.013	19.93	-	0.1	6.69
L2 XL Elbow1	0.07	9.08	0.68	0.032	1.12	0.013	19.93	-	0.1	6.69
L3 XL Elbow1	0.03	9.06	0.85	0.027	1.42	0.027	20.63	-	0.1	15.16
L2 XL Elbow2	0.04	8.51	0.78	0.025	1.56	0.007	20.31	-	0.09	15.89
L3 XL Elbow2	0.02	8.48	0.68	0.029	1.13	0.01	19.64	-	0.09	14.56

2.2. Fracture toughness J-R Curve Method

This method is to predict degradation of mechanical property due to thermal aging embrittlement in the view of fracture toughness. For the loop2 crossover-leg elbow which has the maximum value of percent ferrite, unaged(initial) and aged(saturated) J-R curves were obtained using ANL's correlations applied for static-cast material as shown in Figure 1; for conservative estimation, the maximum value of ferrite content was added up with 6% considering the deviation between measured and calculated values when to calculate the saturation Charpy impact energy Cv_{sat} . The correlations used in this estimation among ANL's outputs are as follows;

$$J_{initial} = 400\,[\Delta a]^{0.40} \qquad (4)$$

$$J_{aged} = 102\,[Cv_{sat}]^{0.28}\,[\Delta a]^{n} \qquad (5)$$

where Δa is crack extension and the exponent n is calculated from

$$n = 0.21 + 0.09 \log_{10}[Cv_{sat}] \qquad (6)$$

Figure 1 shows that a fracture toughness value at a crack depth decreases to a saturated value as it goes thermally aged. A fracture toughness value of 255kJ/m^2 at a crack depth of 2.5mm can be used to differentiate between CASS materials that are nonsusceptable and potentially susceptible to thermal aging embrittlement according to GALL report[3,5]. As shown in Figure 1, The fracture toughness at a crack extension of 2.5mm was calculated to be about 422kJ/m^2 and this is greater enough than the threshold. This result shows that even the highest percent ferrite containing CASS piping has the large enough fracture toughness to thermal aging embrittlement until it is fully aged by operation.

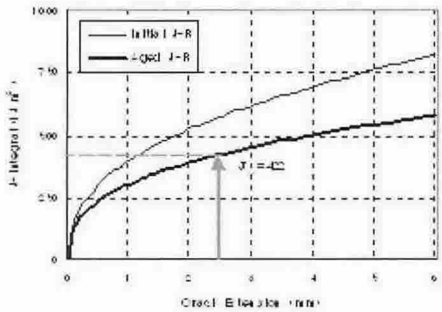

Figure 1. Fracture toughness J-R Curves (initial and fully aged cases for the loop2 crossover-leg elbow)

3. Conclusion

For Kori 3&4 RCS primary pipings manufactured from CASS material having CF-8A Grade, the susceptibility to thermal aging embrittlement was estimated.

As the result, it was found that Kori 3&4 RCS CASS pipings contain so lower ferrite content not to be susceptible to thermal aging embrittlement and have sufficient fracture toughness even when they are fully aged by thermal embrittlement. Therefore, it is concluded that the thermal aging embrittlement effect on Kori 3, 4 RCS CASS pipings is negligible and an additional aging management program on the CASS components need not be organized.

REFERENCES

[1] USNRC Letter to NEI, dated on May 19, 2000.

[2] O. K. Chopra, Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems, NUREG/CR-4513 Rev.1, 1994 .

[3] J. Carey, EPRI TR-106092, “Evaluation of Thermal Aging Embrittlement of Cast Austenitic Stainless Steel Components in LWR Reactor Coolant Systems”, September 1997.

[4] USNRC, Generic Aging Lessons Learned (GALL) Report, NUREG-1801, May 2001.

[5] O. K. Chopra, W. J. Shack, Assessment of Thermal Embrittlement of Cast Stainless Steels, NUREG/CR-6177, 1994.