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Thermal Embrittlement Assessment of RCP Casing

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1. Introduction

CASS(Cast Austenitic Stainless Steel) used in primary pressure-boundary components, such as RCS piping, pump casing, and valve bodies. When CASS materials are exposed to high temperature (i.e.280~320 °C) for a long time, thermal embrittlement can occur[1]. Thermal aging leads to formation of Cr-rich α' phase by spinodal decomposition, and cleavage of this ferrite phase or separation of the ferrite/austenite phase boundary is associated with embrittlement. As license renewal issue, NRC sent the letter to NEI at May 19, 2000. The letter proposed the screening criteria for CASS components' thermal aging embrittlement susceptibility and aging management program. For RCP casing, existing ASME Sec. XI inspection requirement, including ASME Code Case N-481, is adequate, screening for susceptibility to thermal aging is not required[2]. However the susceptibility of thermal embrittlement on K-1 RCP casing which is manufactured by SA351 CF8 is estimated using screening criteria and flaw tolerance evaluation.

2. Methods

2.1 Ferrite Content [1,2]

May 19, 2000 NRC letter provides the criteria which determine the susceptibility of CASS components' thermal aging embrittlement in terms of casting method, molybdenum content, and ferrite content. Ferrite content is calculated by using the Hull's equivalent factors or a method producing an equivalent level of accuracy ($\pm$6% deviation between measured and calculated values).

Delta ferrite content is calculated by following Hull's equivalent factor method.

$$\delta_c = 100.3(Cr_{eq}/Ni_{eq})^2 - 170.72(Cr_{eq}/Ni_{eq}) + 74.22 \quad (1)$$

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

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

Chemical composition data from the pump casing CMTR(Certified Material Test Report) is used.

2.2 Fracture Toughness [1,2]

To differentiate the CASS components between non susceptible and potentially susceptible to thermal aging embrittlement, A fracture toughness value of 255 kJ/m² at a crack depth of 2.5 mm is used. NUREG/CR-4513 provides the method to estimate the fracture toughness of CF-3, CF-8, and CF-8M CASS materials.

Because RCP casing is manufactured by static-cast CF8, following equations are used to estimate the saturated lower-bound fracture toughness.

$$\Phi = \delta_c (Cr + Si)(C + 0.4N) \quad (4)$$

$$\log_{10} C_{Vsat} = 1.15 + 1.136\exp(-0.035\Phi) \quad (5)$$

$$\log_{10} C_{Vsat} = 5.64 - 0.006\delta_c - 0.185Cr + 0.273Mo - 0.204Si + 0.044Ni - 2.12(C + 0.4N) \quad (6)$$

Lower value of C_{Vsat} is used from equation (5) and (6).

$$J_d = 49(C_{Vsat})^{0.52}(\Delta a)^n \quad \text{at RT}$$
$$\text{where} \quad n = 0.20 + 0.12\log_{10}(C_{Vsat}) \quad (7)$$

$$J_d = 102(C_{Vsat})^{0.28}(\Delta a)^n \quad \text{at 290 °C}$$
$$\text{where} \quad n = 0.21 + 0.09\log_{10}(C_{Vsat}) \quad (8)$$
$$\Delta a = crack\ extension$$

2.3 Flaw Tolerance Evaluation

Modeling of RCP casing is performed by ANSYS, finite element analysis modeling program. Material properties are used from ASME B&PV Sec. II Part D. Stress is analyzed considering thermal-pressure weight, deadweight, and normal operation thermal expansion, earthquake weight(OBE, SSE).

Postulated flaw used in this evaluation is located in stress concentrated region and semi-elliptical surface flow with an aspect ratio of 6 to 1. Fatigue crack growth rate is estimated with stress analysis data and upper bound fatigue crack growth rate from EPRI technical report[3].

3. Evaluation & Results

RCP casing is manufactured by static-cast SA351 CF8. Table 1 shows the chemical composition data from CMTR.

Table 1. Chemical composition of casing material (wt%)

No.	Ni	C	Mn	S	Si	Mo	Co	Cr	P
A	9.09	0.05	0.84	0.012	1.32	0	0.13	19.04	0.028
B	8.84	0.06	0.98	0.012	1.33	0	0.14	19.29	0.03

Nitrogen concentration is not appeared in CMTR, so use 0.04 wt%[1].

3.1 Ferrite Content

According to GALL report[2], static-cast and low-molybdenum content(0.5 wt% max) CASS is potentially susceptible to thermal embrittlement only if ferrite content exceed 20%. If ferrite content is below or equal to 20%, it is not susceptible.

Calculated ferrite contents using equation (1)~(3) are 5.8 % and 6.5 % for each A and B casing. These values are much less than the criterion value.

3.2 Fracture Toughness

Fracture toughness value (at crack depth 2.5mm) 255 kJ/m^2 is suggested in GALL report to divide the CASS materials into potentially susceptible and nonsusceptible. If fracture toughness is larger than 255 kJ/m^2, this CASS component is nonsusceptible.

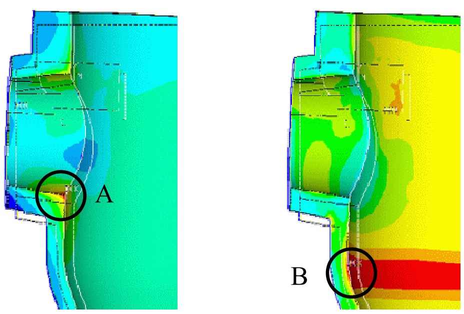
Estimated saturation lower-bound fracture toughness J-R curve is drawn using equation (4)~(8). From the curve, fracture toughness at crack depth value of 2.5 mm is calculated, shown in Table 2. All values are greater than 255 $kJ/m^{2,}$ and nonsusceptible.

Table 2. Saturation fracture toughness of RCP casing at crack depth value of 2.5 mm (kJ/m^2)

RCP No.	Fracture toughness($J_{2.5}$)		GALL
	at RT	at 290 °C	
A	558	885	255
B	525	792	

3.3 Flaw Tolerance Evaluation

Thermal-pressure weight is analyzed conservatively from design base event, because anticipated operational transient and occurrence number is much smaller than this number. Normal operation, exceptional condition, highly improbable condition, and hydrotesting condition are grouped and enveloped.



(a) (b)

Figure 1. Maximum stressed region when (a) nozzle hoop stress, (b) nozzle axial stress is applied

Combination of external weight like deadweight, normal operation thermal expansion, OBE, and SSE are added linearly to calculate the probable maximum applied stress. Figure 1 shows the maximum stressed region. Area 'A' and 'B' are selected for fatigue crack growth assessment.

When postulated flaw depth of 10% of thickness is assumed, final flaw depth and stress intensity factor is 21% and 2.7 $ksi\sqrt{in}$ for 'A', 12% and 1.8 $ksi\sqrt{in}$ for 'B' casing. These stress intensity factors are less than 3.7 $ksi\sqrt{in}$, threshold stress intensity factor for fatigue crack growth of casing material. There is no contribution to fatigue crack growth.

4. Conclusion

Thermal embrittlement susceptibility of CF8 graded static-cast CASS RCP casing was assessed by ferrite content, fracture toughness, and flaw tolerance evaluation. It contains lower ferrite content compare to criterion value, sufficiently high saturation fracture toughness. Although there is no flaw, flaw tolerance with postulated flaw was evaluated. Final crack depth and stress intensity factor is not concern to the end of life.

Thermal aging embrittlement effect on K-1 RCP casing is not significant problem.

REFERENCES

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

[2] NRC, Generic Aging Lessons Learned Report, NUREG-1801 Rev. 1, 2005

[3] J. Carey, EPRI 1000976, Evaluation of Thermal Aging Embrittlement of CASS Components, 2001