Transactions of the Korean Nuclear Society Spring Meeting
Chuncheon, Korea, May 25-26 2006

A Study on Integrity Evaluation of Cast Austenitic Stainless Steel Piping Considering Thermal Aging Embrittlement

Jong Sung Kim(a), Tae Eun Jin(a), Young Jong Kim(b), Hye Young Shin(c), Young Sheop Park(c)
(a) Korea Power Engineering Company, 360-9, Yongin, Kyunggi-do, Republic of Korea, 449-713, kimjs@kopec.co.kr
(b) GNEC Professional Engineer's Office, 150, Daejeon, Republic of Korea, 305-353
(c) Korea Hydro & Nuclear Power, Co., Ltd., 103-16, Daejeon, Republic of Korea, 305-600

1. Introduction

It is necessary to resolve the plant aging issues and maintenance obsolescence for the continued safe operation beyond the original licensed period. To achieve these goals, the evaluation of major components should be required to ensure that aging will be adequately managed. Cast austenitic stainless steel (CASS) was used for reactor coolant (RC) piping in light water reactors (LWRs). However, CASS with more than 14% or 20% ferrite phases has been known to experience a reduction of fracture toughness caused by thermal aging embrittlement, when exposed to reactor opera-ting temperatures, 280~320℃, over long period [1]. In this paper, we have evaluated susceptibility of thermal aging embrittlement, fatigue crack growth and flaw tolerance considering thermal aging embrittlement in order to ensure the structural integrity of CASS RC piping during the continued operation.

2. Susceptibility Evaluation of Thermal Aging Embrittlement

Figure 1 shows schematic drawings of CASS RC piping in Plant A. As shown in Figure 1, RC piping in the Plant A consisted of a hot leg, a cold leg and a crossover leg for each loop. Table 1 presents the shapes and fabrication methods of subparts which construct RC piping. As presented in Table 1, RC piping consisted of four straight pipes and five fittings/elbows for each loop.

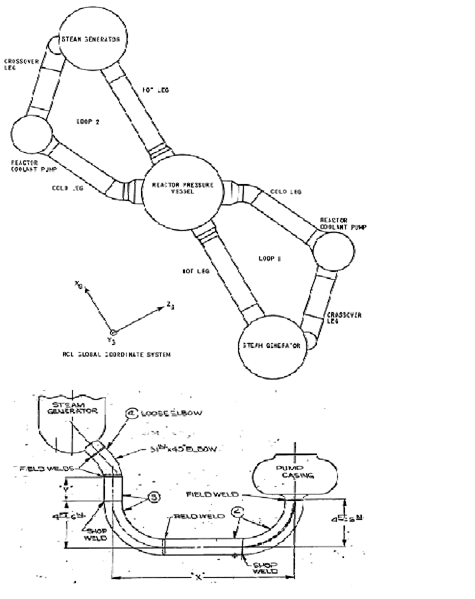

Figure 1. Schematic drawings of RC piping in Plant A

Table 1. Specifications for subparts of RC piping in Plant A

Compo-nent	Subpart (OD-system-loop-subcomponent no.)	Cast method	Number
Hot leg	29-RC-A-1101 (straight)	Centrifugal	1
	29-RC-A-1101 (50°fitting)	Static	2
	29-RC-B-1104 (straight)	Centrifugal	3
	29-RC-B-1104 (50°fitting)	Static	4
Cross-over leg	31-RC-A-1102 (straight)	Centrifugal	5
	31-RC-A-1102 (straight)	Centrifugal	6
	31-RC-A-1102(90°elbow with splitter)	Static	7
	31-RC-A-1102 (90°elbow)	Static	8
	31-RC-A-1102 (40°fitting)	Static	9
	31-RC-B-1105 (straight)	Centrifugal	10
	31-RC-B-1105 (straight)	Centrifugal	11
	31-RC-B-1105(90°elbow with splitter)	Static	12
	31-RC-B-1105 (90°elbow)	Static	13
	31-RC-B-1105 (40°fitting)	Static	14
Cold leg	27.5-RC-A-1103 (straight)	Centrifugal	15
	27.5-RC-A-1103 (35°elbow)	Static	16
	27.5-RC-A-11036 (straight)	Centrifugal	17
	27.5-RC-B-11036 (35°elbow)	Static	18

Table 2 presents the ferrite contents calculated by substituting chemical compositions in CMTR (certifi-cated material test report) into Aubrey's equation [2] and the susceptibility evaluation results derived by comparing them with the screening criteria presented in USNRC Letter [3]. From Table 2, it is identified that one straight pipe and seven fittings/elbows are potential-ly susceptible to thermal aging embrittlement because the ferrite contents exceed screening criteria.

Table 2. Susceptibility evaluation results

No.	Subpart		Ferrite Content (Vol.%)	Screening Criteria (Vol.%)	Susc.
1	Hot leg	Straight pipe	12.58	20	×
3			21.09	20	○
2		50° fitting	14.58	14	○
4			10.82	14	×
5	Cross-over leg	Straight pipe 1	14.16	20	×
6			14.16	20	×
10		Straight pipe 2	17.42	20	×
11			17.42	20	×
7		90° elbow with splitter	16.34	14	○
12			12.99	14	×
8		90° elbow	14.16	14	○
13			14.81	14	○
9		40° fitting	14.58	14	○
14			14.58	14	○
15	Cold leg	Straight pipe	17.81	20	×
17			19.17	20	×
16		35° elbow	13.15	14	×
18			16.72	14	○

3. Flaw Tolerance Evaluation Considering Thermal Aging Embrittlement

In order to ensure the structural integrity of CASS RC piping susceptible to thermal aging embrittlement, two options have been recommended [1]. One is to demonstrate the integrity through enhanced volumetric examination for base metal and another is to perform plant- and component-specific flaw tolerance evaluation considering material property changes due to thermal aging embrittlement. In this study, the latter has been performed because the former has practical problems due to wide examination range.

The final crack sizes at the continued operation completion time(=40 years) are calculated by using the fatigue crack growth evaluation procedure presented in ASME B&PV Code, Sec.XI, App.A, C and L. Table 3 presents final axial crack depths for the various subparts of CASS RC piping. From Table 3, it is identified that the fatigue crack growth isn't significant over the continued operation period.

Table 3. Final axial crack depth for various subparts

Subpart		Initial crack: Depth ratio (%)	Initial crack: Depth (mm)	Final crack depth (mm)	Crack location
Hot leg	50° fitting	12.36	8.7884	10.67	Max. hoop stress generation location in each subpart
	Straight pipe	12.36	8.7884	10.27	
Cross-over leg	40° fitting	11.7	8.9154	10.67	
	90° elbow	11.7	8.9154	11.18	
	90° elbow with splitter	11.7	8.9154	11.18	
Cold leg	35° elbow	12.69	8.7122	10.16	

Failure mode at the continued operation completion time can be changed from fully-plastic fracture (FPF) to ductile fracture (DF) because tensile properties increase and fracture toughness decreases due to thermal aging embrittlement. Therefore, failure mode should be determined by using ASME B&PV Code, Sec.XI, App.C, Article C-4000 because flaw tolerance evaluation method is changed in accordance with failure mode. Table 4 presents failure mode evaluation results for the various subparts of CASS RC piping. From Table 4, it is found that with the exception of 35^o elbow in cold leg, the failure modes of almost all subparts are FPF. If the failure mode is FPF, flaw tolerance has to be evaluated by limit load analysis. The failure mode of 35^o elbow is DF. Elastic-plastic fracture mechanics (EPFM) analysis has to be performed if the failure mode is DF.

Flaw tolerance at the continued operation completion time is evaluated by limit load analysis procedure or EPFM analysis procedure presented in ASME B&PV Code, Sec.XI, Subsec.IWB, IWB-3600 and App.C.

Table 4. Failure mode evaluation results for axial crack

Subpart		Max. SIF at final crack size $K_{I\text{-}max}$ (MPa m$^{0.5}$)	Min. fracture toughness K_{Ic} (MPa m$^{0.5}$)	SC (=K'$_r$/ S'$_r$)	Remark
Hot leg	50° fitting	20.55	203.5	0.177	FPF (limit load analysis)
	Straight Pipe	20.29	203.5	0.175	FPF (limit load analysis)
Cross-over leg	40° fitting	20.51	187	0.192	FPF (limit load analysis)
	90° elbow	20.83	187	0.196	FPF (limit load analysis)
	90° elbow with splitter	20.84	187	0.196	FPF (limit load analysis)
Cold leg	35° elbow	34.61	164	0.272	DF (EPFM analysis)

Note) FPF if SC<0.2. DF if 0.2≤SC<1.8

The limit load analysis is performed for all subparts except for 35^o elbow while the flaw tolerance of 35^o elbow is evaluated by EFPM analysis. Table 5 presents the flaw tolerance evaluation results at the continued operation completion time. From Table 5, it is identified that structural integrity of CASS RC piping, which is susceptible to thermal aging embrittlement, is maintained over the continued operation period because the final crack depth ratios for all subparts are much smaller than allowable crack depth ratios.

Table 5. Flaw tolerance evaluation results for axial crack

Subpart		Final crack depth ratio	Allowable crack depth ratio	Remark
Hot leg	50° fitting	0.150	0.7	Maintenance of Integrity over the continued operation period
	Straight pipe	0.144	0.7	
Cross-over leg	40° fitting	0.140	0.7	
	90° elbow	0.147	0.7	
	90° elbow with splitter	0.147	0.7	
Cold leg	35° elbow	0.148	0.44	

4. Conclusion

A study on integrity evaluation of CASS RC piping was performed considering the change of material properties due to thermal aging embrittlement. From this study, it is found that structural integrity of CASS RC piping is maintained over the continued operation period.

REFERENCES

[1] USNRC, GALL Report, Draft NUREG-1801, 2005.
[2] L.S. Aubrey, et al., STP 756, ASTM, pp.126-164, 1982.
[3] Letter from Christopher I. Grimes, USNRC, License Renewal and Standardization Branch, to Douglas J. Walters, NEI, LR Issue No. 98-0030, 2000.