Proceedings of the Korean Nuclear Society Spring Meeting
Seoul, Korea, May 1998

Fatigue Evaluation on the Inside Surface of Reactor Coolant Pump Casing Weld

Seung Tae Kim and Ki Sung Park

Korea Plant Service and Engineering Co. Ltd.
Technology Development Center
13-1 Heungin-Dong, Jung-Ku
Seoul, Korea, 100-430

Abstract

Metallic fatigue of Pressurized Water Reactor(PWR) materials is a generic safety issue for commercial nuclear power plants. It is very important to obtain the fatigue usage factor for component integrity and life extension. In this paper, fatigue usage was obtained at the inside surface of Kori unit 2, 3 and 4 RCP casing weld, based on the design transient. And it was intended to establish the procedure and the detailed method of fatigue evaluation in accordance with ASME Section III Code. According to this code rule, two methods to determine the stress cycle and the number of cycles could be applied. One method is the superposition of cycles of various design transients and the other is based on the assumption that a stress cycle correspond to only one design transient. Both method showed almost same fatigue usage in the RCP casing weld.

1. Introduction

The major goal of design rules in ASME Section III Code[1], Subsection NB-3000 is to provide protections against two different types of failure :

(1) Protection against catastrophic failure ;

(2) Protection against fatigue.

Assuming that the primary stresses and primary plus secondary stresses meet the allowable stress requirements, the total stress range due to the combined primary plus secondary plus peak stresses is then calculated. The total stress amplitudes for all significant load set pairs are used to enter the fatigue curves in the Section III, Appendices. A load set is defined as a combination of pressure, temperature and force/moment loadings. The allowable number of cycles are obtained from these curves. The Design Specification defines the number of cycles for each loading condition. Knowing the number of design cycles and allowable number of cycles, fatigue usage factors, the ratio of the number of design cycles to the allowable number of cycles for each load set pair(so called "Palmgren - Miners Rule"), can be calculated. The summation of the individual usage factors is called the cumulative usage factor. If the cumulative usage factor is less than or equal to 1.0, the ASME Section III Code requirements for fatigue are satisfied.

Since fatigue usage is a function of stress range of each stress cycle, the determination of its magnitude and the number of cycles is critical in the fatigue evaluation. In the ASME Code rule, there can be two different ways to determine the stress cycle. One method is the superposition of cycles of various design transient, which certainly leads to the most conservative fatigue usage. And the other is to consider the stress cycle produced by each design transient. In this paper, fatigue evaluation was performed on the inside surface of Kori unit 2, 3 and 4 RCP(Reactor Coolant Pump) casing weld by using both methods. Stress data on the RCP casing was taken from Westinghouse stress report[2].

KPS(Korea Plant Service and Engineering Co. Ltd.) is performing the stress analysis of Kori unit 2, 3 and 4 RCP casing and integrity evaluations, such as flaw evaluation, fatigue evaluation described in this paper and LBB(Leak-Before-Break) application. The computer program of these integrity evaluations is now under development and will automatically perform integrity evaluation of primary components and piping if stress data of a location concerned are available. Stress analysis results of RCP casing already have been partially verified by comparing with stress values of Westinghouse stress report.

2. Stresses on the RCP Casing Weld

The model of Kori unit 2, 3 and 4 RCP casing is 93A and 93A-1. Although each unit has different model, the casing geometry is identical, as are the design transients shown in Table 1. The casing material is cast stainless steel, SA351 CF8, 304 type. The finite element model shown in Figure 1 was used to determine the stresses in the pump casing. The loads included thermal, pressure and pipe loads on the suction nozzle and discharge nozzle.

Fatigue evaluation was performed on Cut 1 location shown in Figure 2, because this position experience the highest stress ranges. Each transient produces a peak(maximum stress) and a valley(minimum) stress during the transient. The maximum and minimum stresses at cut 1 location are given in Table 2. The direction of principal stress is assumed to be constant at this location and actually varies little. It should be noted that for the fatigue evaluations all six stress components are considered. However, the local coordinate system used herein approximately matches the principal axes. Therefore, axial stress provides direct information in fatigue usage predictions.

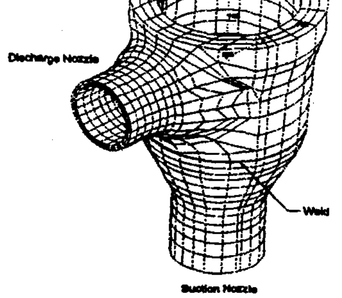

Fig. 1 Finite Element Model of Kori Unit 2, 3 & 4 RCP Casing

Table 1 Summary of Primary Coolant System Transients : Kori unit 2, 3 & 4 Reactor Coolant Pump Casing

No.	Transient Identification	Number of Occurrences
	Normal Condition	
1.	Heatup/Cooldown at 100°F/hr	200
2.	Unit Load/Unload(0~15% of full power)	500
3.	Unit Loading and Unloading at 5% Full Power/Minute	13,200
4.	Step Load Increase and Decrease of 10% Full Pwr	2,000
5.	Large Step Decrease with Steam Dump	200
6.	Feedwater Cycling at Hot Shutdown	2,000
7.	Loop Out of Service	120
8.	Refueling	80
	Upset Condition	
9.	Loss of Load, without Immediate Reactor Trip	80
10.	Loss of Power	40
11.	Partial Loss of Flow, One Pump Only	80
12.	Reactor Trip from Full Power : No Cooldown	230
13.	Reactor Trip with Cooldown : No Safety Injection	160
14.	Reactor Trip with Cooldown and Safety Injection	10
15.	Inadvertent RCS Depressurization	20
16.	Inadvertent Startup of an Inactive Loop	10
17.	Control Rod Drop	80
18.	Inadvertent Safety Injection Actuation	60
19.	Excessive Feedwater Flow	30
	Test Condition	
20.	Turbine Roll Test	10
21.	Cold Hydrostatic Test	5
22.	Primary Side Leak Test	50

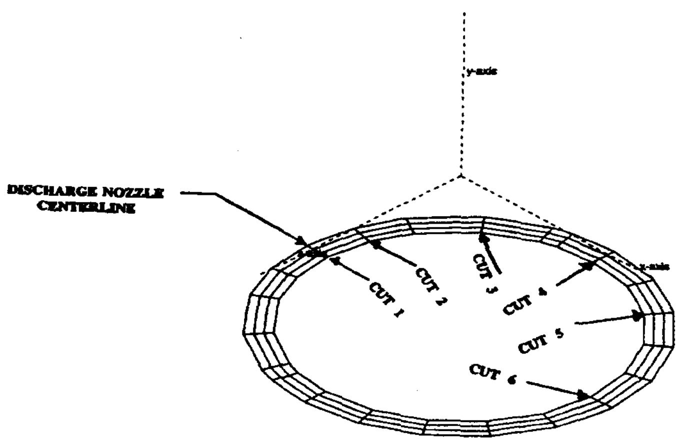

Fig. 2 Location of Cut 1 in the Weld Region of RCP Casing

Table 2 Peak and Valley Stresses of the Design Transients : Axial Stress

No.	Transients	σ_{peak} (ksi)	σ_{valley} (ksi)	No.	Transients	σ_{peak} (ksi)	σ_{valley} (ksi)
Normal Condition				12.	Reactor Trip from Full Power : No Cooldown	12.93	9.57
1.	Heatup/Cooldown at 100°F/hr	16.85	-12.50	13.	Reactor Trip with Cooldown : No Safety Injection	19.49	9.58
2.	Unit Load/Unload (0~15% of full power)	13.18	12.55	14.	Reactor Trip with Cooldown and Safety Injection	34.13	2.39
3.	Unit Loading and Unloading at 5% Full Power/Minute	13.63	11.39	15.	Inadvertent RCS Depressurization	47.87	3.97
4.	Step Load Increase and Decrease of 10% Full Pwr	15.13	-0.44	16.	Inadvertent Startup of an Inactive Loop	13.12	9.03
5.	Large Step Decrease with Steam Dump	14.76	8.52	17.	Control Rod Drop	12.93	10.68
6.	Feedwater Cycling at Hot Shutdown	21.43	8.89	18.	Inadvertent Safety Injection Actuation	13.52	7.55
7.	Loop Out of Service	17.76	12.77	19.	Excessive Feedwater Flow	64.06	-15.10
8.	Refueling	33.71	0.11	**Test Condition**			
Upset Condition				20.	Turbine Roll Test	40.41	1.25
9.	Loss of Load, without Immediate Reactor Trip	15.45	-5.25	21.	Primary and Secondary Side Leak Test	18.24	-1.17
10.	Loss of Power	18.94	3.87	22.	Cold Hydro	17.81	0.00
11.	Partial Loss of Flow, One Pump Only	13.11	7.44				

3. Fatigue Evaluation

3.1 ASME Section III Code : Fatigue Evaluation

For any case in which the directions of the principal stresses at the point being considered do not change during the cycle, fatigue evaluation method and procedure of ASME Section III Code, Subsection NB-3200 are summarized as follows :

(a) Determine the peak and the valley stress of each transient which correspond to the maximum and minimum stress intensity during the transient.

(b) Find the stress intensity range which form each stress cycle of types 1, 2, 3, ..., n, during the service and list them in the order of their magnitude. Call them ΔS_1, ΔS_2, ΔS_3, ..., ΔS_n.

(c) Designate the specified number of cycles which will be repeated during the life of the component as n_1, n_2, n_3, ..., n_n, respectively.

(d) For each type of stress cycle, determine the alternating stress intensity S_{alt} from the following equation (1). Call these quantities S_{alt1}, S_{alt2}, S_{alt3}, ..., S_{altn}.

$$S_{alt} = \frac{1}{2} \Delta S (E_{curve} / E_{analysis}) K_e \quad (1)$$

- Elastic Modulus Correction Factor : E_{curve} / $E_{analysis}$

In order to consider the effect of elastic modulus, multiply S_{alt} by the ratio of the modulus of elasticity given on the design fatigue curve(ASME Section III Code, S-N curve, Figs. I-9.0) to the value of the modulus of elasticity used in the anlysis.

● Plastic Penalty Factor : K_e

The $3S_m$ limit on the range of primary plus secondary membrane and bending stress intensity, S_n, may be exceeded. In this case, S_{alt} is multiplied by the factor K_e, plastic penalty factor, where :

$$\begin{aligned} K_e &= 1.0, \text{ for } S_n \le 3S_m \\ &= 1.0 + [(1-n)/n(m-1)]\,(S_n/3S_m - 1), \\ &\quad \text{for } 3S_m \le S_n \le 3mS_m \\ &= 1/n, \text{ for } S_n \ge 3mS_m \end{aligned} \qquad (2)$$

The values of the material parameters m and n for the various classes of permitted materials are shown in Table 3.

Table 3 Values of m, n, and T_{max} for Various Classes of Materials (ASME Section Ⅲ Code, Table NB-3228.5(b)-1)

Materials	m	n	T_{max}, °F
Carbon Steel	3.0	0.2	700
Low Alloy Steel	2.0	0.2	700
Martensitic Stainless Steel	2.0	0.2	700
Austenitic Stainless Steel	1.7	0.3	800
Nickel-chromium-iron	1.7	0.3	800
Nickel-copper	1.7	0.3	800

(e) For each value S_{alt1}, S_{alt2}, S_{alt3}, ..., S_{altn}, determine the number of allowable cycle by using the applicable design fatigue curve. Call these values N_1, N_2, N_3, ..., N_n.

(f) For each type of stress cycle, calculate the usage factors U_1, U_2, U_3, ..., U_n, from $U_1=n_1/N_1$, $U_2=n_2/N_2$, $U_3=n_3/N_3$, ..., $U_n=n_n/N_n$.

(g) Calculate the cumulative usage factor U from $U=U_1+U_2+U_3+.....+U_n$. which shall not exceed 1.0.

3.2 Fatigue Usage of RCP Casing Weld

Since each transient covers a complete thermal event, two stresses, the maximum and the minimum, characterize a transient event. These are known as the peak and the valley of a transient. The stresses to be used in the fatigue are labeled 1P, 1V, 2P, 2V, ..., etc, where the numbers 1, 2, etc. denote the transient numbers and the subindices P and V denote the peak and the valley stress, respectively, for each transient. Therefore, a total of 44 stresses are considered in this fatigue evaluation. Each stress should be associated with a number of occurrences, exactly equal to the number of occurrences of the corresponding design transient. These sets of data form a stress pool as shown in Table 2 for fatigue evaluation.

The superposition method is to pair up or match up the peaks and valleys from the stress pool. The paring process starts with searching the largest possible stress range from the available stress pool. After the largest stress range is determined, the frequency of this stress cycle equals the smaller of the number of occurrences between the two participating stress states. Meanwhile, the number of occurrences of the participating stress states are reduced by the numbers used in forming the cycle. The number of occurrences left for the next cycle paring is reduced accordingly. When the remaining number of occurrences of a particular stress state is zero, it is no longer considered in the rest of the fatigue evaluation. The process is repeated for the next largest stress range based on the remaining available data in the stress pool. On the other hand, considering the stress cycles originated from each design transient, the number of occurrences is equal to the number of each transient.

The material properties used in the evaluations are based on T=350°F, approximately the average temperature of the room temperature and the operating temperature. ASME Code[3] material data of 304 stainless steel at 350°F are given in Table 4. The elastic modulus correction factor is calculated as 28.3/26.75=1.058 on $E=28.3\times10^3$ ksi at room temperature.

Table 4 ASME Code Material Data of 304 Stainless Steel at 350°F.

Material (350°F)	Allowable Design Stress, Sm (ksi)	Elastic Modulus (ksi)	Yield strength (ksi)
304 stainless steel	19.35	26.75×10^3	21.6

The stress ranges determined by the superposition method are arranged in order of its magnitude and the result of fatigue evaluation is given in Table 5. It showed that cumulative usage factor was 0.0131 at Cut 1 location. The other calculation was made considering the stress cycle of each design transient. The fatigue evaluation result from this assumption is given in Table 6. The cumulative usage factor, CUF=0.0130, was obtained at the same location and this value is almost the same as the CUF value calculated by using the former method. It is revealed that fatigue usage of Kori unit 2, 3 & 4 RCP casing weld is very small and therefore much allowance exists for fatigue damage.

Table 5 Fatigue Usage Evaluation at the Inside Surface of Kori unit 2, 3 & 4 RCP Casing Weld : Cut 1 Location (Considering all the possible stress cycle)

Transient Mates	Stress Range (ΔS_p)	Cycles Used (n)	Plastic Penalty Factor(K_e)	Alternating Stress (S_{alt}, ksi)	Allowable Cycles (N_f)	Usage Factor ($U_f=n/N_f$)
19P - 19V	79.16	30	2.212	92.63	2307	0.0130
15P - 1V	60.37	20	1.133	36.18	199253	0.0001
20P - 1V	52.19	10	1.0	27.99	$> 10^6$	0.0000
14P - 1V	46.63	10	1.0	24.67	$> 10^6$	0.0000
⋮						⋮
Total(CUF)						**0.0131**

Table 6 Fatigue Usage Evaluation at the Inside Surface of Kori unit 2, 3 & 4 RCP Casing Weld - Cut 1 Location (Considering the stress cycle of each transient)

Transient Mates	Stress Range (ΔS_p)	Cycles Used (n)	Plastic Penalty Factor(K_e)	Alternating Stress (S_{alt}, ksi)	Allowable Cycles (N_f)	Usage Factor ($U_f=n/N_f$)
19P - 19V	79.16	30	2.212	92.63	2307	0.0130
15P - 15V	43.90	20	1.0	23.22	> 10^6	0.0000
20P - 20V	39.16	10	1.0	20.72	> 10^6	0.0000
8P - 8V	33.60	80	1.0	17.77	> 10^6	0.0000
⋮						⋮
Total(CUF)						**0.0130**

4. Conclusion

This paper established the procedure and the detailed method of fatigue evaluation in accordance with ASME Section III Code. At the inside surface of RCP casing weld, fatigue usage was obtained and two different methods to determine the stress cycle were used. Both methods showed little difference of cumulative usage factor. The CUF values was 0.0131 and 0.0130, respectively. This value revealed enough allowance for excessive fatigue damage beyond the service life. In other words, RCP casing weld could be anticipated to sustain its operating integrity.

References

1. "Rules for Construction of Nuclear Power Plant Components," Section III, Division 1, 1995 ASME Boiler and Pressure Vessel Code, American Society of Mechanical Engineers.
2. W. H. Bamford, et. al., "Stresses for Use in Flaw Evaluation for Kori Units 2, 3 and 4 Reactor Coolant Pump Casing Weld," Westinghouse Stress Report, WCAP-14841, Feb., 1997.
3. "Materials Part D-Properties," Section II, 1992 ASME Boiler and Pressure Vessel Code, American Society of Mechanical Engineers.