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Mitigation of Over-conservatism in Fatigue Analysis of the Pressurizer Surge Line

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1. Introduction

The U.S. Nuclear Regulatory Commission (NRC) issued draft regulatory guide DG-1144 [1] in July 2006, entitled “Guidelines for Evaluating Fatigue Analysis Incorporating the Life Reduction of Metal Components Due to the Effects of the Light-Water Reactor Environment for New Reactors.” This draft guide demands to perform fatigue analysis in accordance with the draft NUREG/CR-6909 report (Effect on Fatigue Life of Reactor material for LWR Coolant Environments) [2] for carbon and low-alloy steels, and austenitic stainless steel materials. In March 2007, NRC formally issued Reg. guide 1.207 [3] which demands to perform fatigue analysis in accordance with the final NUREG/CR-6909 report [4]. Reviewing these documents it is found that in case of austenitic stainless steel and Ni-Cr alloy the new design fatigue curve is much more severe than present curve and will increase the cumulative usage factor (CUF) 4 to 5 times of the present value. In particular, detailed analysis for pressurizer surge line which is made of stainless steel is needed and mitigation of over-conservatism included in present fatigue analysis procedures is absolutely required.

In this study, thus, the mitigation method for over-conservatism in the present fatigue analysis procedure for the pressurizer surge line is studied.

2. Analytical Method

2.1 General procedure

The peak thermal stress in fatigue analysis procedure of ASME Code Section Ⅲ NB-3650 is basically founded on uniformity of the temperature and thermal stress distributions along the pipe circumference, which is inadequate when thermal stratification occurs, and in that case partial modification of the formula is inevitable. The formulas for fatigue analysis given in ASME Code Section Ⅲ NB-3650 are as follows.

$$Sn = C_1 \frac{PoDo}{2t} + C_2 \frac{Do}{2I} Mi + C_3 E_{ab} |\alpha_a T_a - \alpha_b T_b| \leq 3Sm \tag{1}$$

$$Sp = K_1 C_1 \frac{PoDo}{2t} + K_2 C_2 \frac{Do}{2I} Mi + K_3 C_3 E_{ab} |\alpha_a T_a - \alpha_b T_b| + K_3 \frac{E\alpha}{2(1-\nu)} |\Delta T_1| + \frac{E\alpha}{1-\nu} |\Delta T_2| \tag{2}$$

$$Se = C_2 \frac{Do}{2I} Mi^{*} \leq 3Sm \tag{3}$$

$$Sn' = C_1 \frac{PoDo}{2t} + C_2 \frac{Do}{2I} M' + C_3' E_{ab} |\alpha_a T_a - \alpha_b T_b| \leq 3Sm \tag{4}$$

$$S_{alt} - \frac{1}{2} KeSp \tag{5}$$

Figure 1 illustrates the fatigue analysis procedure of ASME Code Section Ⅲ NB-3650.

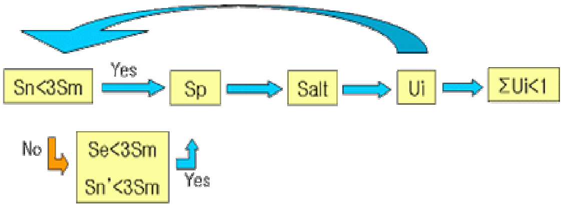

Figure 1. Fatigue analysis procedure of ASME Code Section Ⅲ NB-3650

2.2 Moment loads for stratified flow

Surge line connects pressurizer and primary pipe, and its horizontal section is subject to thermal stratification problem which induces additional moment loads due to the temperature difference between upper and lower part of the pipe section. The moment loads given in the design specification for this condition is usually calculated with a conservative assumption. If thermal fluid flow analysis method using three-dimensional finite element model of the surge line were used, this over-conservatism will be mitigated. To obtain the moment loads in pipe for thermal stratification condition we used FLUENT code and ANSYS code, the first one to get the temperature distribution and the second one to get the thermal stresses and moment loads. The section locations for pipe loads calculated are shown in Figure 2.

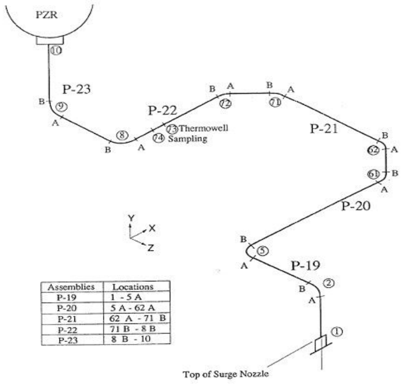

Figure 2. Locations of calculated pipe loads

Table 1 shows the calculated pipe loads and compares them with the design specification loads. As shown in the table, the calculated-to-specification ratio for each section ranges from 0.28 to 0.59, which means that the moment loads are reduced about 41% to 72%. As thermal stratification load is one of the main loads in surge line fatigue analysis, the calculated loads are expected to contribute in considerable reduction of fatigue usage factor.

Table 1. Pipe loads by thermal stratified flow (Heatup Transient)

Location	Thermal Stratified Flow (Heatup Transient)		
	Calculated [in-kips]	UCN 5&6 [in-kips]	Calculated-to-UCN Ratio
	MI	MI	MI
1	1021	2761	0.37
2A	1466	2499	0.59
2B	1157	2443	0.47
H1Y	920	2449	0.38
5A	954	2453	0.39
5B	888	2433	0.36
61A	1065	2498	0.43
61B	1149	2511	0.46
62A	1353	2568	0.53
62B	1369	2558	0.54
H2Y	1327	2532	0.52
71A	1115	2478	0.45
71B	1045	2468	0.42
H3Y	942	2449	0.38
72A	806	2436	0.33
72B	683	2428	0.28
8A	829	2483	0.33
8B	1070	2538	0.42
9A	1294	2509	0.52
9B	1284	2390	0.54
10	1164	2286	0.51

3. Simulated Cases and Results

Table 2 summarizes the CUFs for four simulated cases at each piping location. The simulation was performed by utilizing a fatigue analysis module programmed with Microsoft Excel and its VBA (Visual Basic for Application). In case G1 the curve C in Fig.I-9.2.2 of the ASME B&PV Code Section III [5] was used for conservatism. For case G2 we included the curve B which gives more realistic and longer fatigue life. In case G3 we set the ratio of elasticity modulus that is usually applied to the alternating stress before entering the fatigue curve in accordance with the requirement specified in NB-3200 of reference 5 to be unity, because there is no such requirement specified in NB-3600. And in case G4 we applied the calculated moment loads as explained above instead of the design specification loads. The mitigating condition of each case is applied in addition to the previous case.

Table 2. Summary of cumulative usage factors

Condition	Location	**G1**	**G2**	**G3**	**G4**
Homogeneous Flow	Pipe	0.05124	0.04855	**0.02835**	0.02835
	Elbow	0.04597	0.04412	**0.02394**	0.02394
	RTD Nozzle	0.86045	0.74525	**0.37623**	0.37623
	Sampling Nozzle	0.50853	0.41090	**0.22367**	0.22367
Stratified Flow	Pipe	0.06805	0.06291	0.06291	**0.05389**
	Elbow	0.39698	0.39428	0.39428	**0.01672**
	RTD Nozzle	0.42829	0.42720	0.42720	**0.17424**
	Sampling Nozzle	0.28530	0.28139	0.28139	**0.12162**

For homogeneous flow condition, G2 shows small but meaningful effect and G3 shows significant effect on reducing the CUF values. G4 has no effect for homogeneous flow condition.

For stratified flow condition, G2 shows little effect, and G3 shows no change because the modulus of elasticity in cases G1 and G2 was already set to be equal to that value given in Fig. I-9.2.2. G4 shows significant reduction in CUF values, as expected. Especially the elbow part shows great reduction by utilizing the calculated stratification moment loads.

4. Conclusion

In this study, available points for mitigation of the over-conservatism included in present fatigue analysis procedure of the pressurizer surge line were drawn out by reviewing the technical backgrounds and simulating four test cases utilizing these points. The first one is the present procedure, and the remaining cases utilize the realistic fatigue curve, the unity ratio of elasticity modulus, and the reduced stratification moment loads.

The fatigue analysis of surge line was performed using the formulas and procedures specified in ASME B&PV Code. The procedure was formulated by using Microsoft Excel and its VBA. The realistic fatigue curve has relatively small effect on CUF. The unity ratio of elasticity modulus has significant effect for homogeneous flow condition, and the reduced stratification moment loads have significant effect for stratified condition.

REFERENCES

[1] U.S.NRC, Guidelines for Evaluating Fatigue Analysis Incorporating the Life Reduction of Metal Components due to the Effects of the Light-Water Reactor Environment for New Reactors, Draft Regulatory Guide DG-1144, July 2006.

[2] U.S.NRC, Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials, Draft Report for Comment, NUREG/CR-6909, ANL-06/08.

[3] U.S.NRC, Guidelines for Evaluating Fatigue Analysis Incorporating the Life Reduction of Metal Components due to the Effects of the Light-Water Reactor Environment for New Reactors, Reg. Guide 1.207, March 2007.

[4] U.S.NRC, Effect of LWR Coolant Environments on the Fatigue Life of Reactor materials, Final Report, NUREG/CR-6909, ANL-06/08, February 2007.

[5] ASME Boiler and Pressure Vessel Code, SectionⅢ, 2004 Edition.