Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2015

Structural Evaluation of a PGSFR Steam Generator for a Steady State Condition

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1. Introduction

Steam generator system (SGS) in a sodium-cooled fast reactor (SFR) converts sub-cooled water to superheated steam by transferring heat from the intermediate sodium to water/steam, and provide superheated steam during normal power operation[1]. Steam generator (SG) is a heat exchanger as well as structural barrier between liquid sodium and water/steam and thus the strict structural integrity is required to prevent the design failure.

In this study, design loads for design condition and normal operating steady state condition were classified and the structural analyses for each design loads were carried out. And, structural integrities under each service level were evaluated according to ASME design code[2].

2. Structural Design and Evaluation

2.1 Structural Features and Numerical Modeling

The SG is a vertically oriented, shell-and-tube heat exchanger which has a sodium-to-water counterflow with straight heat transfer tubes. The IHTS hot sodium enters the SG outer shell inlet nozzle and passes through the inlet windows. The sodium then flows down over the tube bundle and out through the lower outlet windows and flows in the IHTS cold leg pipe. Both ends are half spherical chambers providing steam and feedwater. The expansion bellows on the main shell is applied to provide a large flexibility to compensate for thermal expansion difference between tube bundle and shell. The tubes are supported horizontally by 15 tube support plates (TSP). The SG including tubes is made of 9Cr-1Mo-V steel which has high capacity in heat transfer and low thermal expansion. The overall size of the unit is 29.88m high and 2.7m diameter.

The finite element model for an SG was made by using ANSYS[3] program and a 1/4 sectional symmetric model is used as shown in Fig. 1. The element types for structural and thermal analyses are SOLID185 and SOLID70 elements, respectively and BEAM188 is used for the tubes. The general assumptions for the structural analyses are as follows.

- IHTS piping nozzles and TSPs are not included and thus SG has a structural symmetry.
- The effective material properties with solid plate model are applied for both perforated tubesheets.
- Circumferential temperature is constant at a given vertical level.
- The outer surface of SG shell is an adiabatic condition.
- The sodium temperature in SG shell increases linearly in vertical direction.
- The reduced beam elements equivalent with tubes in total mass are applied.
- Both steam header and feedwater chamber are about 20cm thick.

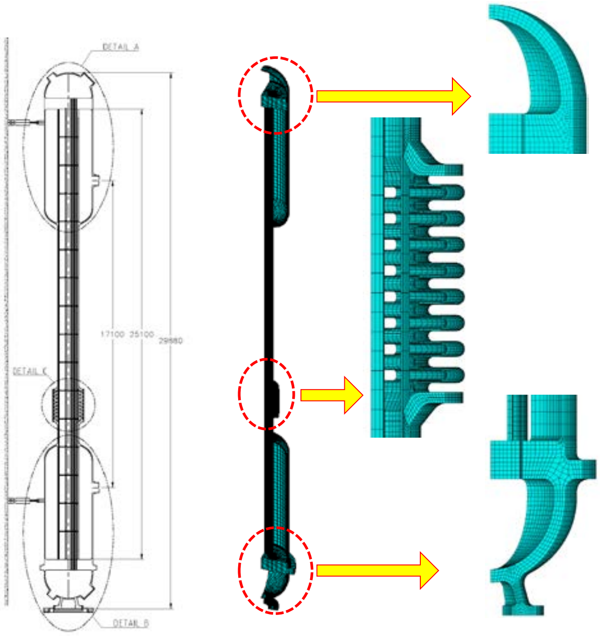

Fig. 1. Front view drawing and FE model of SG structure.

2.2 Loading and Boundary Conditions

Though the reactor system generally experiences kinds of operating events, the steady state condition of normal operating event in this study is considered for the operating loading. The primary loads on SG are dead weight, design pressure and hydrostatic pressure. The design pressure on SG shell is set to be 3.5 MPa by virtue of sodium-water reaction (SWR) pressure. Other design pressures in steam header and feedwater chamber are 18.4 MPa and 20.0 MPa, respectively. The fluid weight is applied as an equivalent pressure on the lower tubesheet, feedwater chamber and upper outer shell.

The secondary load is caused by the temperature distribution at the full power condition of normal operating event. At the steady state condition, the SG shell has a linear temperature variation vertically from 332℃ to 528℃ and the feedwater chamber and steam header have constant temperature at 240℃ and 503℃, respectively. Table 1 shows the loading conditions in each service level.

Vertical bottom support condition and symmetric boundary conditions at both side sections of FE model are applied.

Table I: Loading Conditions for Service Levels

Service Level	Event name	Service time	# of cycle	Max./Min. Temp.(℃)
Design Condition	- Dead weights - Hydrostatic pressure - SWR	60	-	555/431
A & B	- Dead weights - Hydrostatic pressure - SWR - SS full power	60	240	528/240

2.3 Structural Analyses

The structural analyses by using ANSYS program are carried out for 4 primary loads independently. Figure 2 shows the stress intensity distributions for each condition. The major critical sections for each loading condition are structural discontinuity or fillet junction. The maximum stress is 153 MPa at steam header junction by the steam pressure, which is relatively high comparing with other loading results but maybe acceptable because of its high strength. The stresses at critical sections are linearized independently and then they are summarized in each stress component.

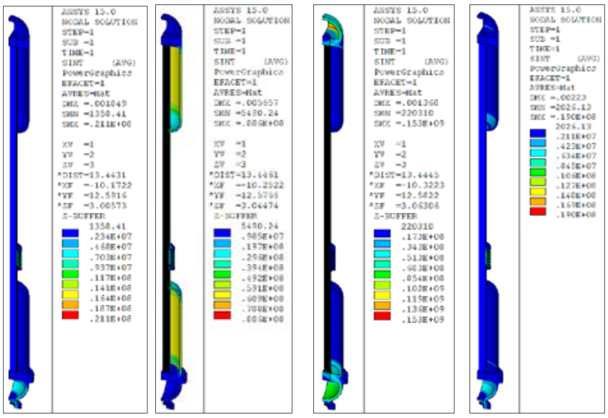

Fig. 2. Stress intensity distributions for primary loads which are dead weight, SWR pressure, feedwater/steam pressure & hydrostatic pressures, and fluid weight from left to right.

For the secondary load, the temperature distribution is calculated by the heat transfer analysis at the full power condition. The temperature distribution from FE analysis is almost same as the steady state condition as shown in Fig. 3. The maximum thermal stress intensity is 124 MPa at the fillet junction of the feedwater plenum and lower tubesheet. It is caused by the temperature difference between IHTS cold sodium temperature(332℃) and feedwater temperature(240℃).

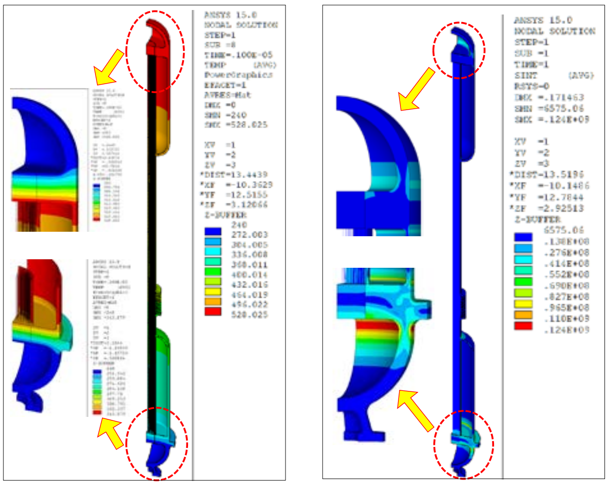

Fig. 3. Temperature distribution and thermal stress intensity distribution at steady state condition

2.4 Structural Integrity Evaluations

From the stress analyses, three sections are selected for the structural integrity evaluation; Section-A(feedwater plenum), Section-B(lower outer shell), and Section-C(steam header). The service levels under evaluation are both design condition and normal operating steady state condition. The stress results are classified and summarized each component of stress under each service level. The design criteria for design condition are membrane stress (P_m, P_L) and bending stress (P_b) for primary loading. Table 2 shows the results of structural integrity by using SIE-Div.5 code for the design condition[4]. The most critical section caused by steam pressure is section-C, a steam header but all sections including section-C satisfies the design criteria with design margin over 30%.

Table 2: Evaluation Results of Structural Integrity under Design Condition

Sections	Nodes	Linearized Stress	Calculated Stress (MPa)	Allowable Stress (MPa)		Margin	Temperature (℃)
Section-A Feedwater chamber	Inner	Pm	60.1	So	170.3	1.83	431.0
		PL + Pb	121.2	1.5So	255.5	1.11	
	Outer	Pm	60.1	So	170.3	1.83	431.0
		PL + Pb	114.7	1.5So	255.5	1.23	
Section-B Lower outer shell	Inner	Pm	28.1	So	97.8	2.48	555.0
		PL + Pb	22.2	1.5So	146.7	5.61	
	Outer	Pm	28.1	So	97.8	2.48	555.0
		PL + Pb	42.7	1.5So	146.7	2.44	
Section-C Steam header	Inner	Pm	51.3	So	97.8	0.91	555.0
		PL + Pb	112.2	1.5So	146.7	0.31	
	Outer	Pm	51.3	So	97.8	0.91	555.0
		PL + Pb	101.0	1.5So	146.7	0.45	

Additional structural integrity is evaluated for the normal operating steady state condition. The design criteria for service Level A & B are primary stresses, secondary stress (Q), thermal ratcheting, and use-fracture sums(USF_m, USF_b) with P_m and P_L+P_b. Table 3 shows the results of the structural integrity evaluation at the full power condition. Because the SWR event is not included in the normal operating cycle, the stresses from SWR event is not added in stress calculation. The results show that all sections satisfy the design criteria and design margin of Section-C is the smallest. For the loading conditions, Section-A is under the most severe internal pressure in SG and thermal stress is also the most in it. But, its design margin is more than that of Section C. It is because the operating temperature of Section-A is much less than that of Section-C. Therefore, the high temperature region like steam header is required to have sufficient strength against primary load.

Table 3: Evaluation Results of Structural Integrity under Normal operating Steady State Condition

Sections	Nodes	Linearized Stress	Calculated Stress (MPa)	Allowable Stress (MPa)		Margin	Temperature (°C)
Section-A Feedwater chamber	Inner	PL + Pb + Pe + Q	245.9	3Sm	581.9	1.37	240.7
		Thermal Ratcheting	124.1	y*Sy	2352.2	17.95	
	Outer	PL + Pb + Pe + Q	123.9	3Sm	581.6	3.69	248.8
		Thermal Ratcheting	119.6	y*Sy	2352.2	18.67	
Section-B Lower outer shell	Inner	PL + Pb + Pe + Q	128.3	3Sm	568.9	3.43	329.1
		Thermal Ratcheting	98.4	y*Sy	6162.8	61.63	
	Outer	PL + Pb + Pe + Q	111.5	3Sm	568.1	4.10	331.8
		Thermal Ratcheting	111.8	y*Sy	6148.6	54.00	
Section-C Steam header	Inner	Pm	51.6	Smt	116.6	1.26	503.3
		PL + Pb	114.8	KSm	217.7	0.90	
		PL + Pb/Kt	102.1	St	116.6	0.14	
		UFS(t/tm)	t=525600	tm	1842900	0.29	
		UFS(t/tb)	t=525600	tb	818460	0.64	
	Outer	Pm	51.6	Smt	114.8	1.22	505.2
		PL + Pb	12.6	KSm	216.5	16.18	
		PL + Pb/Kt	8.1	St	114.8	13.17	
		UFS(t/tm)	t=525600	tm	1816100	0.29	
		UFS(t/tb)	t=525600	tb	2704300	0.19	

3. Conclusions

The structural analyses of a steam generator are carried out and its structural integrity under the given service levels is evaluated per ASME Code rule. The design loads according to design condition and normal operating steady condition are classified and stresses calculated from stress analyses are linearized and summarized in their stress components. As a result, the SG structure satisfies with design criteria for both service levels. Though the steam header is designed as a thick hemisphere, its design margin is not so high in spite of just steady state condition. Thus, additional evaluation by considering various operating events will be followed.

Acknowledgement

This study was supported by the National Research Foundation of Korea grant funded by the Korea government (Ministry of Science, ICT and Future Planning

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