Structural Integrity Evaluation of SALUS PHTS Pump for Level A Service Loadings

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1. Introduction

SALUS (Small, Advanced, Long-Cycle and Ultimate Safe SFR) is a 100 MWe long-cycle reactor based on a sodium-cooled fast reactor (SFR), currently in the conceptual design phase. The SALUS Primary Heat Transport System (PHTS) pump is a component that circulates the PHTS sodium coolant. In this study, the structural integrity of the SALUS PHTS pump for level A service loadings is evaluated. The stresses induced by dead weight, operating pressure, and thermal loads are calculated through Finite Element (FE) analysis, and the structural integrity of the PHTS pump are analyzed over the plant's lifetime using the ASME B&PV Code Section III [1].

2. Evaluation of Structural Integrity of the PHTS Pump for Level A Service Loadings

2.1 Finite Element Model

Fig. 1 shows the FE model of the SALUS PHTS pump. FE modeling and analysis were performed with ANSYS 2019 [2]. The structural analysis used SOLID185 (8-node structural solid) and MASS21 elements, while the thermal analysis used SOLID70 (8-node thermal solid) elements. The material used for the PHTS pump is type 316 stainless steel.

While the structural configuration exhibits 1/4 symmetry, the boundary conditions for thermal analysis lose the symmetry due to the inclined surface of the internal vessel that separates the hot pool and the cold pool [3]. However, this asymmetry is mitigated by the heat transfer between the hot and cold pools. For the convenience of analysis, the average liquid level contacting the internal vessel and the PHTS pump was considered as a reference for distinguishing the boundary conditions between the hot and cold pools. Based on this assumption, a 1/4 partial model with symmetric boundary conditions was used for all analyses. Considering the support state of the pump head plug fixed to the reactor head, the vertical displacement of the plug contact surface was constrained.

The level A service loadings on the PHTS pump are dead weight, operating pressure, and thermal loads generated during the reload operation - 100% power operation - reload operation cycle. The effect of buoyancy was conservatively neglected, and a gravitational acceleration of 9.81 m/s^2 was applied in the analysis of the dead weight load. The operating pressure acting on the diffuser position was conservatively assumed to be 0.9 MPa. The analyses of dead weight and operating pressure loads were performed under a temperature of 21 °C. The thermal stress analysis was sequentially conducted after heat transfer analysis to calculate the stresses induced by thermal loads. The convective heat transfer coefficients around the PHTS pump were set as follows: 10,000 $W/m^2 \cdot °C$ for the liquid sodium region with high-speed

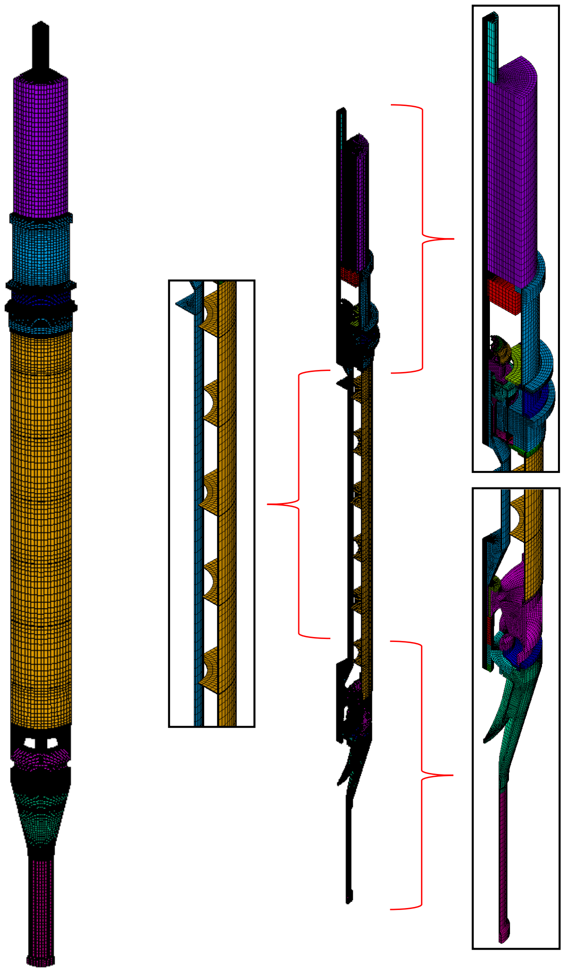
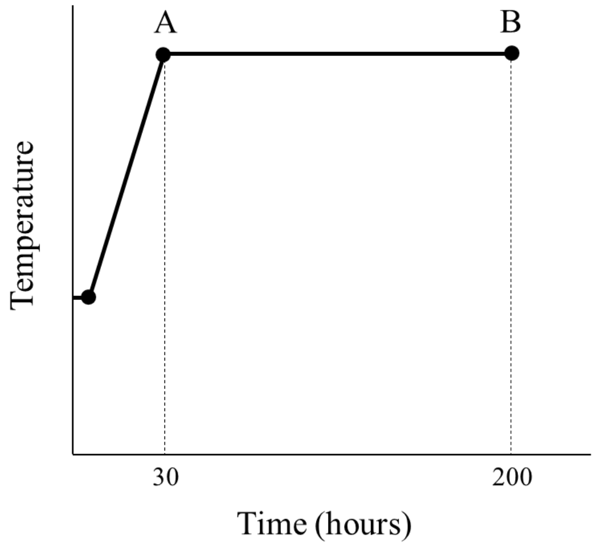
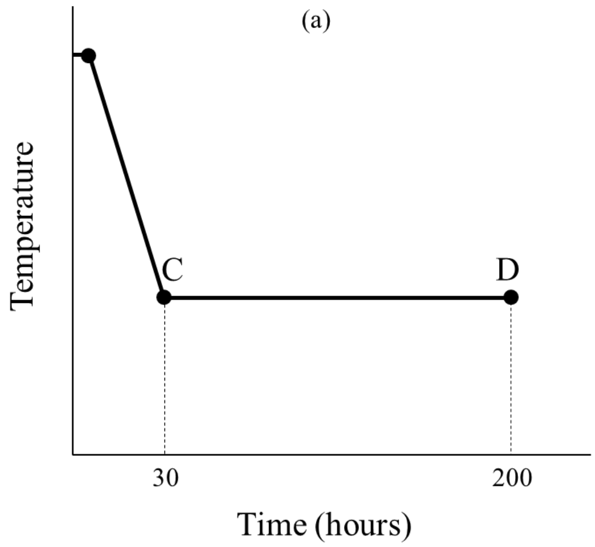


Fig. 1. Finite element model of PHTS pump.

flow, 100 W/m^2·°C for the liquid sodium region with low-speed flow, 3 W/m^2·°C for the gas region in the stagnant zone, and 20 W/m^2·°C for the gas region in the circulating zone. In the heat transfer analysis, two types of transient analyses were conducted as shown in Fig. 2: reload operation - heat-up - 100% power operation and 100% power operation - cool-down - reload operation. Each heat-up and cool-down phase was set to last 30 hours. The design life of the SALUS reactor is 60 years, and the refueling cycle is 20 years. During this 20-year period, a total of 13 reactor shutdowns were assumed, including refueling, control rod assembly replacement and maintenance, and unplanned shutdowns. Accordingly, a total of 39 cycles were assumed for the SALUS design life of 60 years.



(a)



(b)

Fig. 2. Temperature-time transition curve used for (a) heat-up and (b) cool-down transient analysis.

2.2 Structural Analysis Results

Figs. 3 and 4 show the distributions of stress intensities obtained from the analysis of dead weight and operating pressure loads. Both analyses show that the highest stress intensities occur in the bellows located in the upper part of the PHTS pump, with values of 82.4 MPa and 67.2 MPa, respectively.

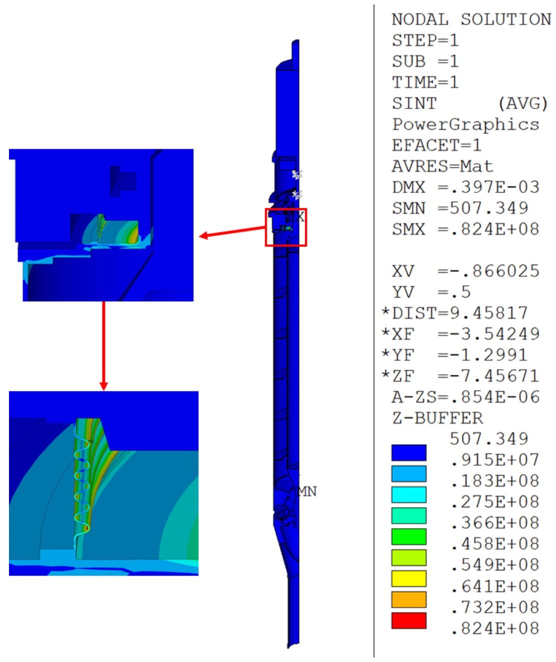


Fig. 3. Stress intensity distribution calculated from FE analysis of dead weight load.

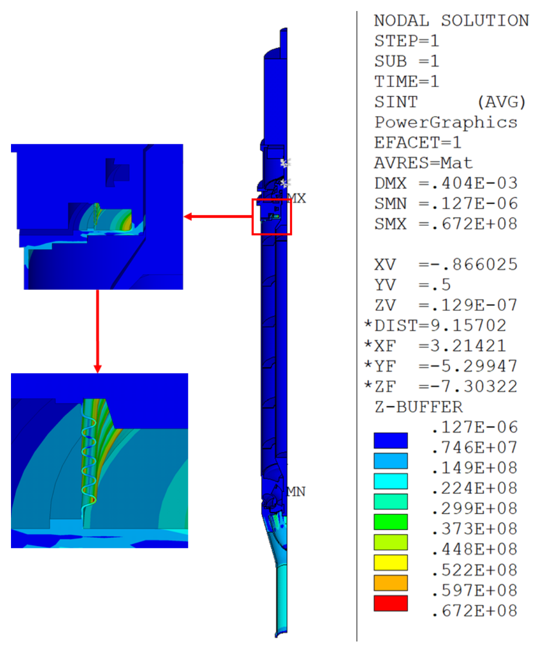


Fig. 4. Stress intensity distribution calculated from FE analysis of operating pressure load.

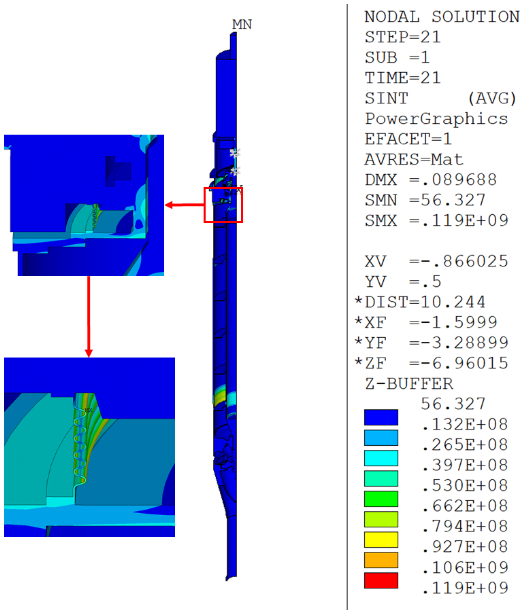


Fig. 5. Stress intensity distribution at the time of maximum thermal stress.

Fig. 5 illustrates the stress distribution at the time when the maximum thermal stress intensity occurs during the reload operation-100% power operation-reload operation cycle. Once again, the highest stress intensity is observed in the bellows located in the upper part of the PHTS pump.

2.3 Structural Integrity Evaluation

As shown in Fig. 6, the stress classification lines (SCLs) were selected at the locations of the bellows in the upper part of the PHTS pump, where the highest stress intensities were observed in each analysis.

The structural integrity of the SALUS PHTS pump was evaluated according to ASME B&PV Code Section III, Division 5. For the Type 316 stainless steel material used in the PHTS pump, specific design criteria of ASME code are applied based on the metal temperature:

Metal temperature below 425 °C: HBA code
Metal temperature equal to or above 425 °C: HBB code

The design margin is defined as follows:

Design Margin = (Allowable Stress/Calculated Stress) – 1

The design target is to secure a design margin of 15% for the main structures and components of the SALUS Nuclear Steam Supply System (NSSS). Since the temperatures at the selected points for the SCLs were all below 425 °C, the evaluation was conducted according to the requirements of Div. 5-HBA. The structural integrity evaluation was performed by combining the analysis results for dead weight and operating pressure loads with the thermal stress analysis at points A&C, A&D, B&C, and B&D, as shown in Fig. 2. The results using the A&D point showed the lowest design margin at all evaluation points, with a minimum design margin of 99.2% as listed in Table I. Therefore, the PHTS pump satisfies the target design margin of 15% for level A service loadings.

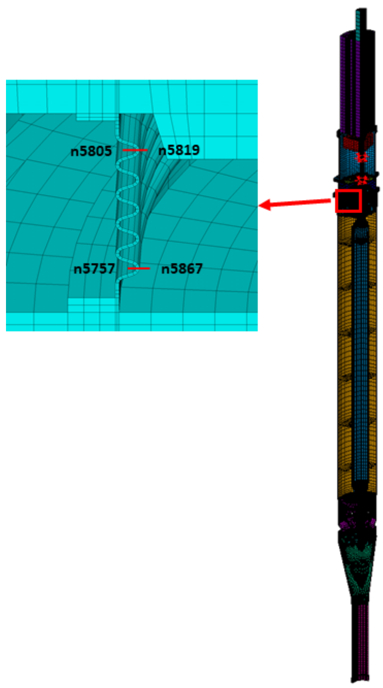


Fig. 6. Location of SCLs of PHTS pump.

Table I: Structural integrity assessment results of PHTS pump for level A service loadings

SCL	Nodes	Items	Calculated Values	Allowable Limits	Margin	Temp. (°C)
1	5805	$\Delta(P_L+P_b+P_e+Q)$ (MPa)	1.98E+02	$3S_m$ = 4.14E+02	1.09E+00	100.5/ 109.2
		Thermal Ratcheting (MPa)	1.40E+02	Y^*S_y = 2.84E+03	1.93E+01	
		Fatigue Damage	2.52E-05	1	3.97E+04	
	5819	$\Delta(P_L+P_b+P_e+Q)$ (MPa)	2.08E+02	$3S_m$ = 4.14E+02	**9.92E-01**	100.6/ 109.2
		Thermal Ratcheting (MPa)	1.47E+02	Y^*S_y = 2.68E+03	1.73E+01	
		Fatigue Damage	0.00E+00	1	∞	
2	5757	$\Delta(P_L+P_b+P_e+Q)$ (MPa)	1.92E+02	$3S_m$ = 4.14E+02	1.16E+00	105.1/ 129.3
		Thermal Ratcheting (MPa)	1.33E+02	Y^*S_y = 2.68E+03	1.91E+01	
		Fatigue Damage	2.11E-05	1	4.74E+04	
	5867	$\Delta(P_L+P_b+P_e+Q)$ (MPa)	2.00E+02	$3S_m$ = 4.14E+02	1.07E+00	105.1/ 129.3
		Thermal Ratcheting (MPa)	1.39E+02	Y^*S_y = 2.48E+03	1.68E+01	
		Fatigue Damage	0.00E+00	1	∞	

3. Conclusion

The structural integrity of the PHTS pump was evaluated through three-dimensional FE analysis for level A service loadings. The evaluated loads included the pump's dead weight, operating pressure, and thermal loads during the reload operation - 100% power operation - reload operation cycle. Based on each analysis, the section with high stress intensity was identified, and the structural integrity of the PHTS pump was evaluated according to ASME B&PV Code Section III, Division 5 HB criteria. The minimum design margin for level A service loadings was calculated to be 99.2%, satisfying the design target of 15%.

ACKNOWLEDGEMENT

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