Study on Improving Structural Integrity of SALUS Reactor Enclosure System

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***Keywords :** SALUS, reactor enclosure system, structural analysis, structural integrity

1. Introduction

Small, Advanced, Long-cycled and Ultimate Safe SFR (SALUS) is a sodium fast reactor (SFR) being developed by KAERI, and the reactor enclosure system (RES) of SALUS consists of a reactor vessel (RV), reactor head (RH), reactor support structure (RSS), and containment vessel (CV), etc. Inside the reactor vessel, the inner vessel (IV) and core assembly are installed. The reactor head is equipped with two primary heat transfer system pumps (PHTS pumps) to circulate the sodium coolant, 4 intermediate heat exchangers (IHXs) for heat exchange of the primary and secondary sodium coolant, and 4 decay heat exchangers (DHXs) to remove the decay heat inside the reactor vessel. These major structures act as the primary load on reactor enclosure system. Since reactor enclosure system of SALUS contains hot liquid sodium coolant, the hydrostatic pressure of the sodium coolant acting on the reactor vessel and the thermal load at the location of the steep thermal gradient are also major loads.

In this study, the structural analysis of the reactor enclosure system of SALUS for level A service loading was performed, and the structural integrity evaluation was performed according to ASME B&PV Code Section 3 [1]. In addition, design modifications of the reactor enclosure system to improve the structural integrity were presented and reviewed.

2. Structural Analysis and Integrity Evaluation

2.1 Finite Element Analysis model

The reactor enclosure system of SALUS consists of the following major structures: reactor vessel, reactor head, reactor support structure, and containment vessel, as shown in Figure 1. The reactor enclosure system structures are composed of two materials: Type 316SS for the reactor vessel, reactor head, and reactor support structure, and 2(1/4) Cr-1MO steel for the containment vessel. The finite element analysis model of the reactor enclosure system is simplified to an axisymmetric structure as shown in Figure 2, taking into account the geometry [2].

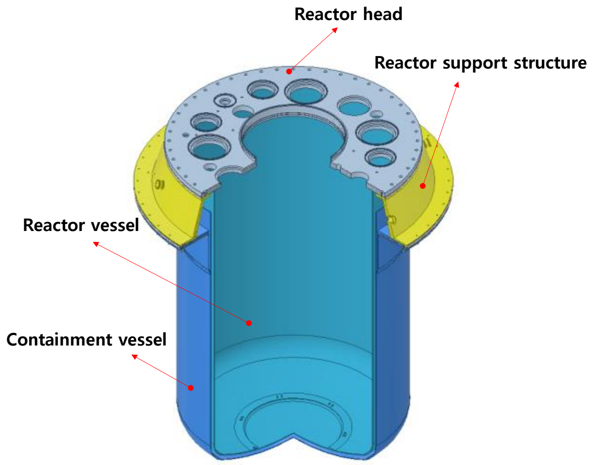


Fig. 1. Reactor enclosure system of SALUS

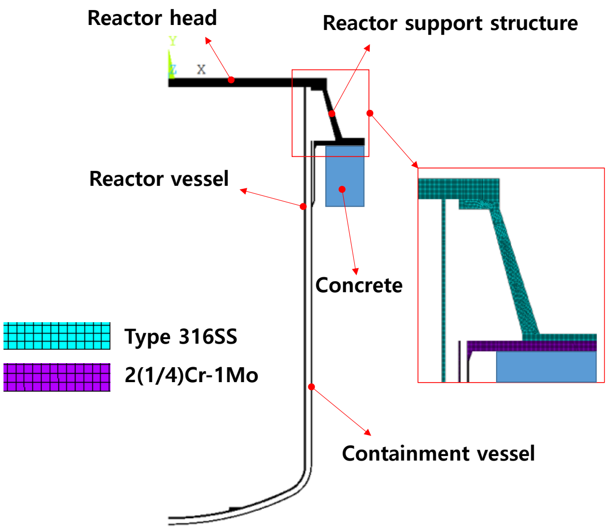


Fig. 2. Finite element analysis model of SALUS RES

2.2 Boundary conditions

The RES is a structure supported on concrete by reactor support structure as shown in Figure 2, and is subjected to primary loads (Load1~Load4) and thermal loads (Load5) as shown in Table 1. Where, the load is for level A service loading (refueling and 100% power operation).

The thermal load was applied directly to the RES surface using the RES surface temperature distribution calculated from the computational fluid dynamics

(CFD) analysis [3]. The temperature distribution of RV and CV calculated by CFD analysis is shown in Figure 3.

Table 1: Level A service loading

Load1	Weight of RV, RH, RSS and CV
Load2	Weight of components supported on RH and intermediate sodium
Load3	Weight of internal structure
Load4	Sodium hydrostatic pressure
Load5	Thermal load (refueling and 100% power operation)

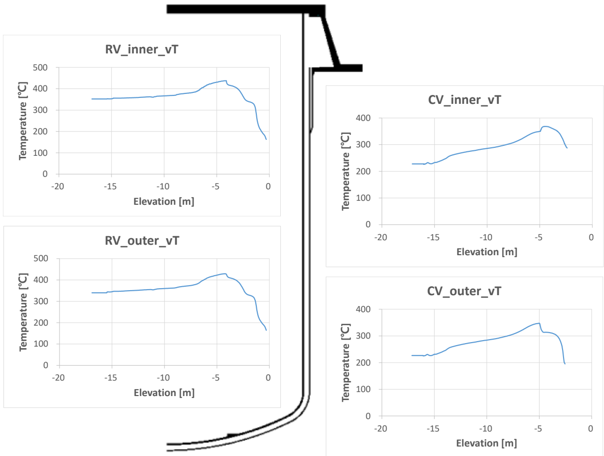


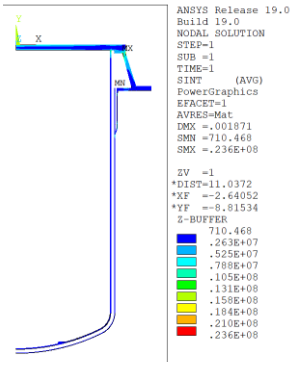
Fig. 3. Temperature distribution of RV and CV

2.3 Structural analysis – Case 1

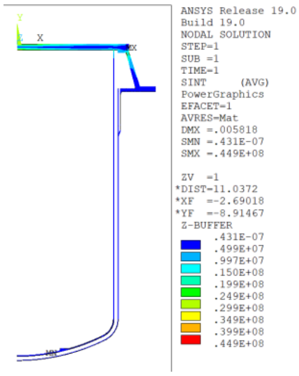
The primary stress intensity distribution results for primary loads are shown in Figure 4.

To analyze heat transfer due to thermal load, transient analysis was performed assuming heat-up and cool-down operation cycle. Heat-up operation is performed in the order of refueling operation - heat-up operation - 100% power operation, and cooling operation is performed in the order of 100% power operation - cool-down operation - refueling operation. It is assumed that the heat-up and cool-down operation is the same for 30 hours. SALUS has a design life of 60 years and a refueling cycle of 20 years. Assuming 13 shutdowns in 20 years, 39 heat-up and cool-down cycles are assumed to occur in 60 years.

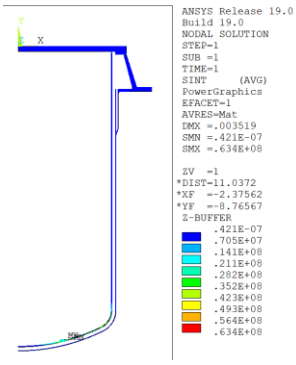
The temperature distribution and thermal stress intensity distribution for thermal load are shown in Figure 5 and 6. As shown in Fig. 5 and 6, the highest thermal stresses are generated near the support flange on the top of the containment vessel, and high thermal stresses are also generated on the top of the reactor vessel.



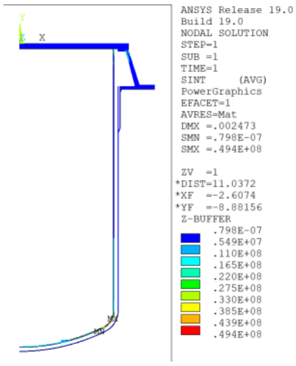
(a) Load1



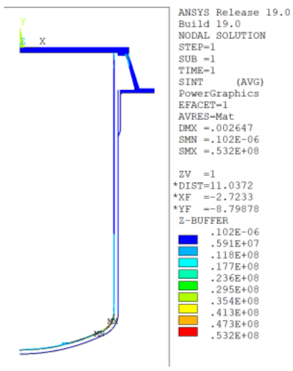
(b) Load2



(c) Load3



(d) Load4
(100% power operation)



(e) Load4(refueling operation)

Fig. 4. Primary stress intensity distribution of RES for primary loads (Case 1)

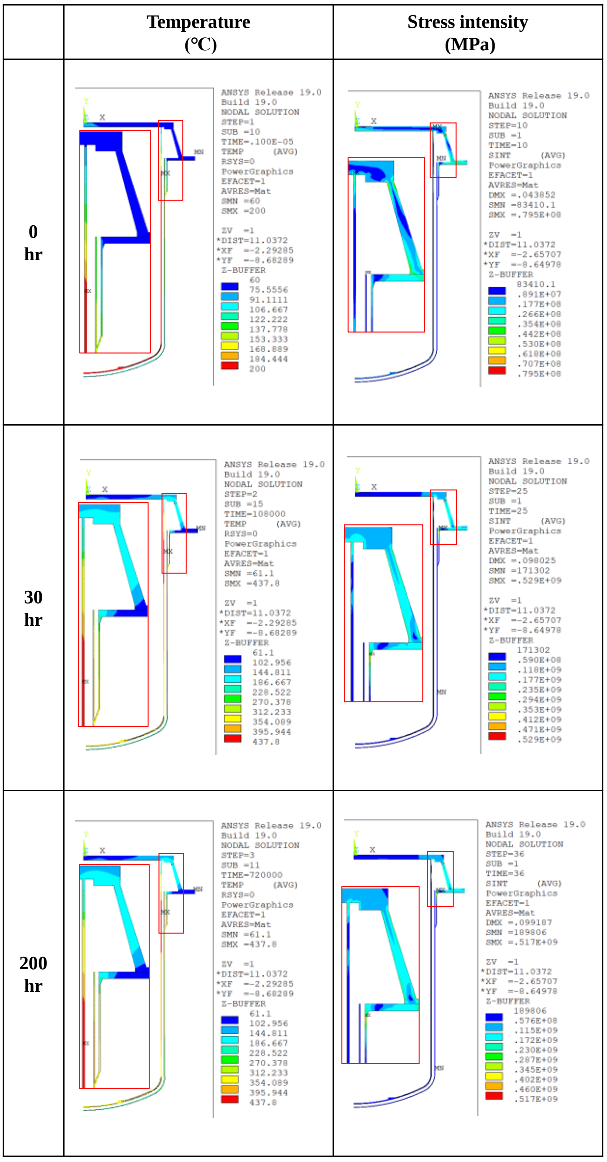


Fig. 5. Temperature and thermal stress intensity distribution of RES for heat-up operation (Case 1)

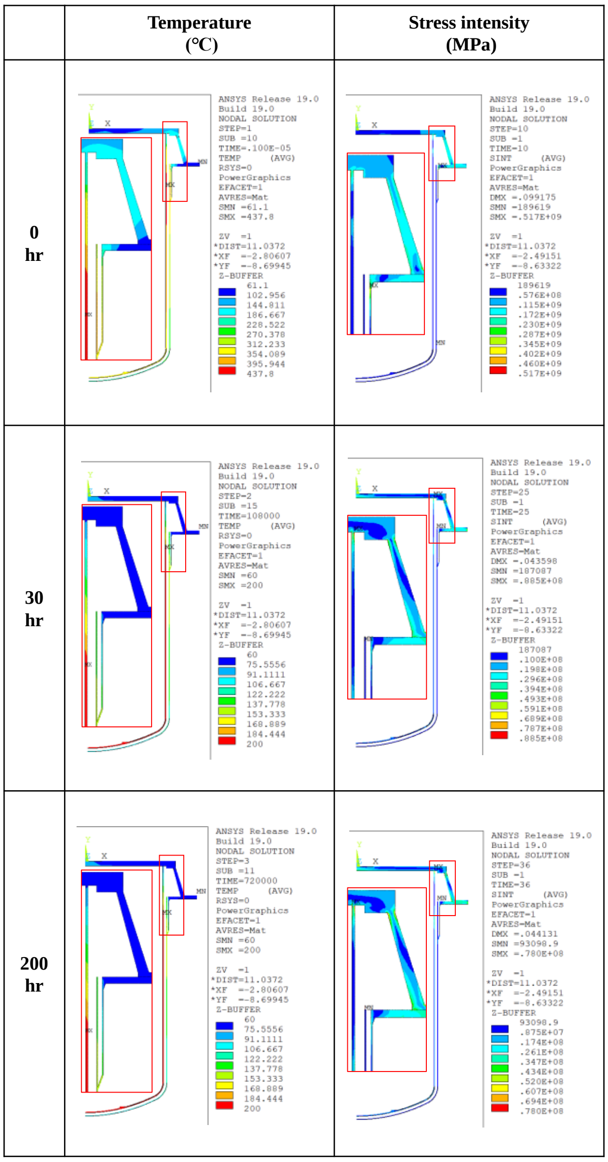


Fig. 6. Temperature and thermal stress intensity distribution of RES for cool-down operation (Case 1)

2.4 Structural analysis – Case 2

To reduce the high thermal stresses near the CV flange and the temperature of the concrete section where the RES is supported, the structural analysis was performed by applying insulation structures and radiation shielding as shown in Figure 7.

CFD analysis was performed to derive the RES surface temperature distribution for the revised RES design. As shown in Figure 8, the maximum temperature at the top of the CV is reduced by about 50% compared to Case1, and the temperature gradient is also reduced. On the other hand, the maximum temperature in the upper part of the reactor vessel is increased.

The primary stress intensity distribution for the primary load is shown in Figure 9, and the temperature distribution and thermal stress intensity distribution for the thermal load are shown in Figure 10 and 11. As shown in Figure 10 and 11, it can be seen that the temperature of the structure close to the concrete has decreased and the temperature gradient has been alleviated due to the effect of applying the insulation structure. Also, the thermal stress near the containment vessel support flange was reduced as shown in Figure 10. However, it can be seen that the maximum temperature of the reactor vessel has increased and the thermal stress in the upper part of the reactor vessel has increased due to the installation of the insulation structure, which limits the heat release from the reactor vessel.

2.5 Structural Integrity Evaluation

The structural analysis results of Case 1 and 2 were evaluated for structural integrity according to ASME B&PV Code Section III. For the structural integrity evaluation, 2 evaluation sections with high stresses were selected as shown in Figure 12. The results of the structural integrity evaluation for Case 1 and 2 are shown in Tables 2 and 3, respectively. As shown in Table 2, it can be seen that the structural integrity of the containment vessel near the support flange is not satisfied in Case 1. On the other hand, as shown in Table 3, it can be seen that the structural integrity of Case 2 is satisfied in all evaluation sections including the containment vessel near the support flange. However, in the case of the upper part of the reactor vessel, the design margin is reduced in Case 2 compared to Case 1.

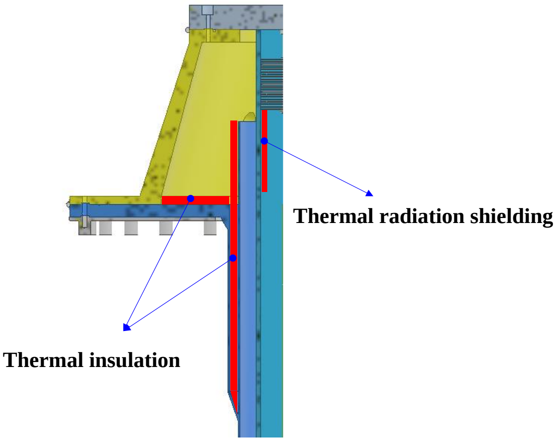


Fig. 7. Insulation structures and thermal radiation shielding applied to RES

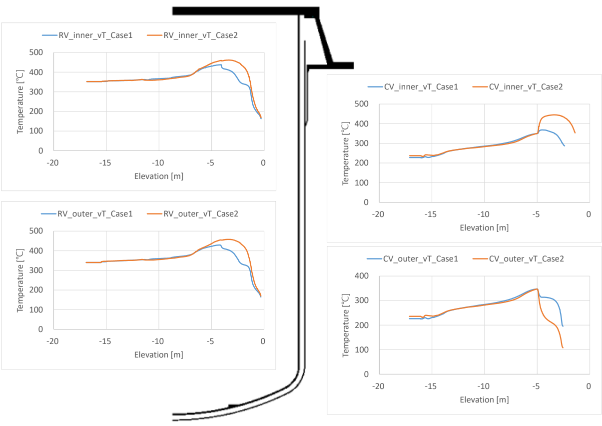
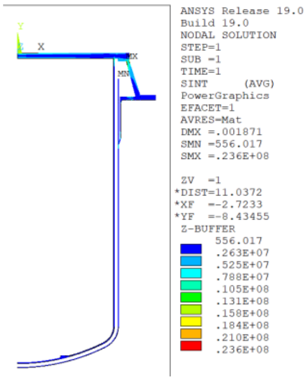
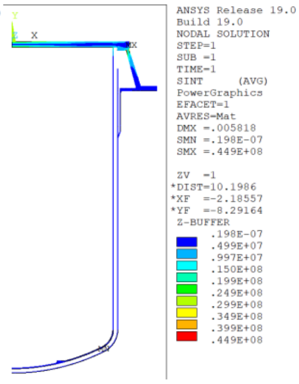


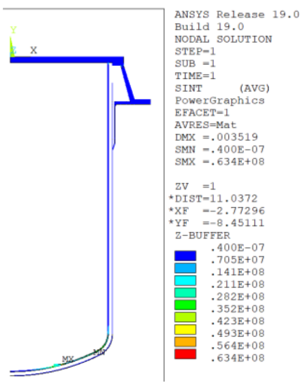
Fig. 8. Temperature distribution of RES (Case1, Case2)



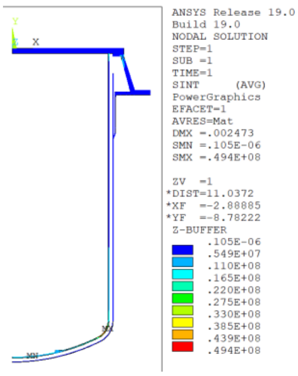
(a) Load1



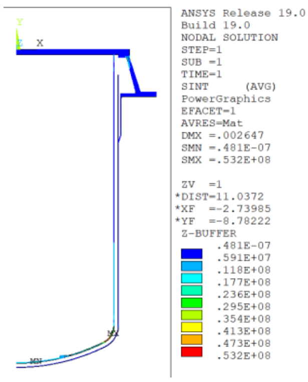
(b) Load2



(c) Load3



(d) Load4
(100% power operation)



(e) Load4(refueling operation)

Fig. 9. Primary stress intensity distribution of RES for primary loads (Case 2)

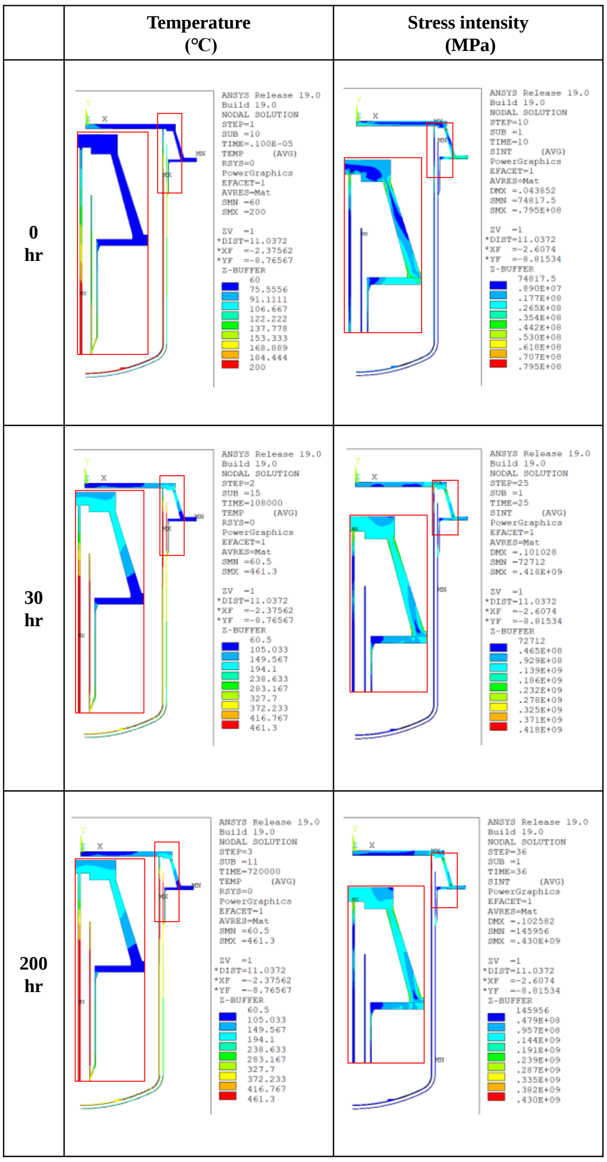


Fig. 10. Temperature and thermal stress intensity distribution of RES for heat-up operation (Case 2)

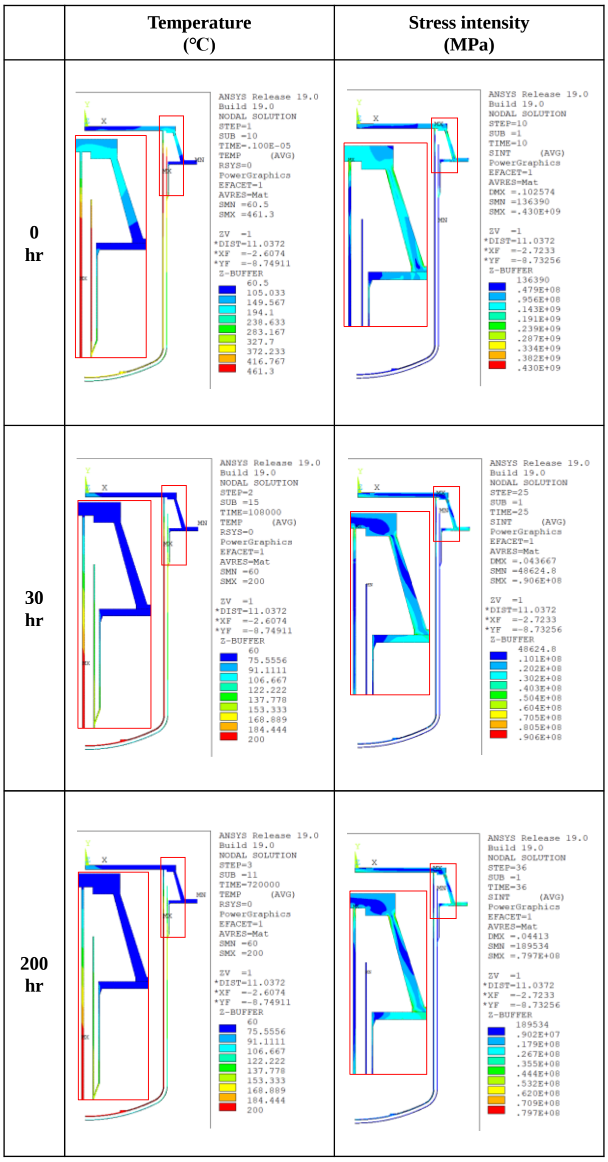


Fig. 11. Temperature and thermal stress intensity distribution of RES for cool-down operation (Case 2)

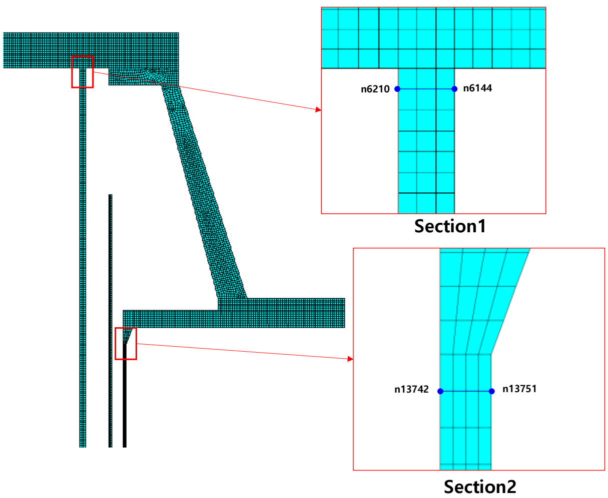


Fig. 12. Structural integrity evaluation sections of RES

Table 2: Structural integrity evaluation results of RES for level A service loading (Case 1)

Sec.	Nodes	Items	Calculated value	Allowable value	margin	Temp Min/Max.
1	6210	Δ(PL+Pb+Qm+Qb) [MPa]	2.46E+02	3Sm = 4.12E+02	6.75E-01	73.7/165.0
		Fatigue damage	5.33E-05	1.00E+00	1.87E+04	
		Thermal ratchet [MPa]	2.47E+02	Y*Sy = 7.03E+02	1.85E+00	
	6144	Δ(PL+Pb+Qm+Qb) [MPa]	1.93E+02	3Sm = 4.12E+02	1.13E+00	74.7/166.7
		Fatigue damage	1.39E-04	1.00E+00	7.21E+03	
		Thermal ratchet [MPa]	2.99E+02	Y*Sy = 4.49E+02	5.02E-01	
2	13742	Δ(PL+Pb+Qm+Qb) [MPa]	4.80E+02	3Sm = 3.81E+02	-2.07E-01	83.4/228.8
		Fatigue damage	3.26E-03	1.00E+00	3.06E+02	
		Thermal ratchet [MPa]	4.80E+02	Y*Sy = 4.57E+03	8.51E+00	
	13751	Δ(PL+Pb+Qm+Qb) [MPa]	3.97E+02	3Sm = 3.82E+02	-3.73E-02	74.8/233.5
		Fatigue damage	2.08E-03	1.00E+00	4.80E+02	
		Thermal ratchet [MPa]	3.97E+02	Y*Sy = 4.76E+03	1.10E+01	

Table 3: Structural integrity evaluation results of RES for level A service loading (Case 2)

Sec.	Nodes	Items	Calculated value	Allowable value	margin	Temp. Min/Max
1	6210	Δ(PL+Pb+Qm+Qb) [MPa]	3.50E+02	3Sm = 4.12E+02	1.75E-01	73.7/170.1
		Fatigue damage	3.45E-04	1.00E+00	2.89E+03	
		Thermal ratchet [MPa]	3.51E+02	Y*Sy = 6.90E+02	9.67E-01	
	6144	Δ(PL+Pb+Qm+Qb) [MPa]	2.97E+02	3Sm = 4.11E+02	3.83E-01	74.7/173.6
		Fatigue damage	1.39E-04	1.00E+00	7.21E+03	
		Thermal ratchet [MPa]	2.99E+02	Y*Sy = 4.49E+02	5.02E-01	
2	13742	Δ(PL+Pb+Qm+Qb) [MPa]	1.85E+02	3Sm = 3.84E+02	1.08E+00	83.4/131.4
		Fatigue damage	4.87E-05	1.00E+00	2.05E+04	
		Thermal ratchet [MPa]	1.85E+02	Y*Sy = 4.78E+03	2.49E+01	
	13751	Δ(PL+Pb+Qm+Qb) [MPa]	1.92E+02	3Sm = 3.86E+02	1.01E+00	74.8/130.0
		Fatigue damage	1.16E-04	1.00E+00	8.59E+03	
		Thermal ratchet [MPa]	1.92E+02	Y*Sy = 4.99E+03	2.50E+01	

3. Conclusions

In this study, a finite element analysis model of SALUS RES was constructed, and structural analysis and structural integrity evaluation were performed for level A service loading. In the case of Case 1, where no insulation structure was installed, high thermal stresses were generated at the containment vessel near the support flange, and it was confirmed that the structural integrity was not satisfied. In order to improve this, Case 2, a design with an additional insulation and shielding structures, was proposed. As a result of the structural analysis of Case 2, it was confirmed that the thermal stress of the containment vessel near the support flange was reduced and the structural integrity was satisfied. However, in the case of the upper part of the reactor vessel, although the structural integrity was satisfied, the design margin was reduced compared to Case 1. It is necessary to conduct a follow-up study on this in the future.

ACKNOLEDGEMENT

This study was supported by the Ministry of Science and ICT through its National Research Fund Program (NRF-2021M2E2A1037872).

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