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Structural Integrity Evaluation of Intermediate Heat Exchanger under a Design Condition

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1. Introduction

The SALUS (Small, Advanced, Long-cycle and Ultimate Safe SFR) which a 100MWe SFR-based advanced power generation reactor with a long fuel cycle is under development at KAERI. Basically the SALUS design adopts the legacy design technologies of PGSFR which was developed to demonstrate transmutation capability of TRU so that most SALUS SSCs' design concepts and arrangements are similar to these of PGSFR.

In the SALUS, four cylindrical-shaped intermediate heat exchangers (IHXs) are arranged in the PHTS (Primary Heat Transfer System) to transfer heat generated from primary sodium to secondary sodium. Since the IHX is classified as a Safety Class I component, and is subjected to high-temperature operation(design temperature: 520℃) in creep region, it should be designed and constructed with nuclear grade and elevated temperature design rules of ASME code.

In this study, the structural analysis of IHX under a design condition was performed and its numerical structural integrity was evaluated based on the ASME BPV Sec. III Division 5 HB[1].

2. Structural Analysis

In this section, the general assumptions and boundary conditions for the structural analysis are described. The analysis results include the maximum stress intensities and deflections for each loading condition under a design condition.

2.1 General Assumptions

The general assumptions for the structural analysis are as follows:

a. A 1/2 symmetric model is used for the structural analysis.
b. 1050 EA tubes are assumed to be three co-axial cylinders with same mass/volume as the tube assembly for a simplification of analysis.
c. The buoyancy force of primary coolant and the primary and secondary sodium jet forces are ignored.
d. The effects of the static pressure for the primary and secondary sodium are ignored.
e. The secondary sodium weights at the lower chamber and upper tubesheet are applied as an equivalent pressure.
f. The weight of a thermal insulation material inserted into the annulus region between the IHX inner cylinder and thermal shield cylinder is ignored.
g. In the analysis, it is assumed that the bottom of IHX supporter is fixed vertically and allows for radial expansion.

2.2 Analysis Model

Fig. 1 shows the geometric shape of IHX and Fig. 2 is its finite element model (FEM) made by ANSYS 18.0 [2]. A 1/2 symmetric model is used in the numerical simulations, and SOLID185 elements (8-node structural solid element) for the structural analysis is used.

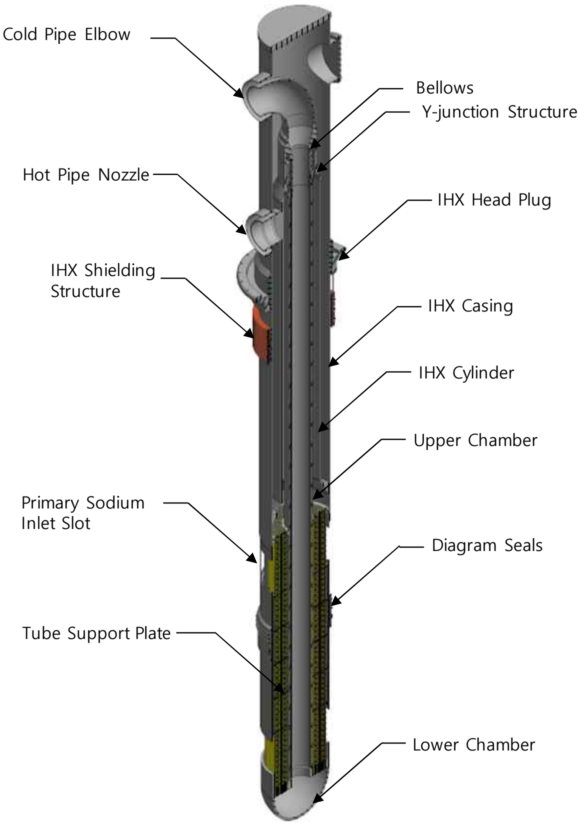


Fig. 1. Section view of IHX.

2.3 Boundary Conditions

IHX is vertically supported on the reactor head with the Y-junction structure so that the fixed condition is applied at its bottom, and its radial expansion is allowed because the reactor head and IHX supporter are radially expanded simultaneously. In addition, since the finite element model is a 1/2 symmetric model, symmetric boundary conditions are also added. The gravity force is applied at the vertical direction for the dead weight calculation. Fig. 3 shows the structural boundary conditions for the dead weight analysis.

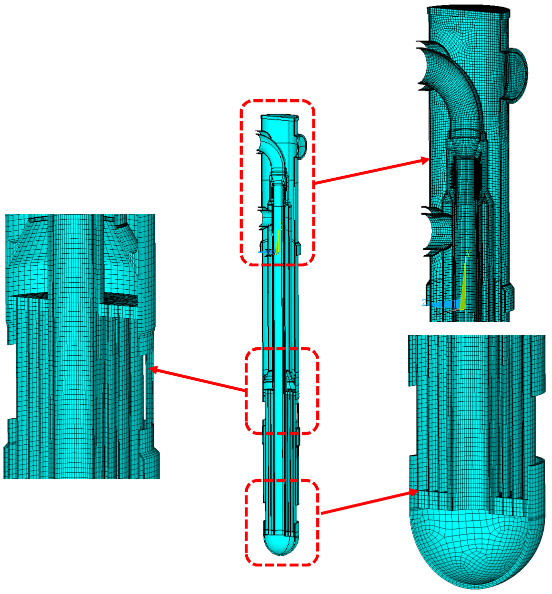


Fig. 2. Finite element model of IHX.

2.4 Loading Conditions

In the design condition, the primary loads (equals to mechanical loads) subjected to IHX are identified as its dead weight, design pressure, and secondary sodium weight.

2.4.1 Dead Weight

For the conservative analysis, the dead weight of IHX is considered in an atmosphere temperature 21°C condition. Fig. 3 shows the loading condition for the dead weight. The gravity force 9.8 m/s^2 is applied to the vertical direction of IHX.

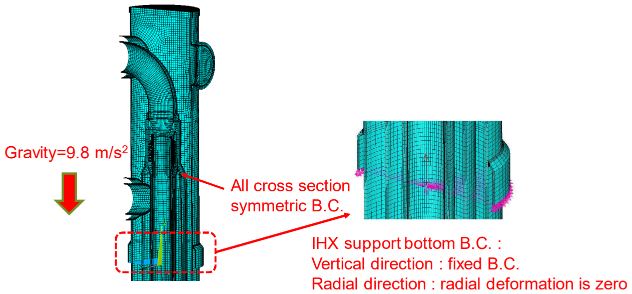


Fig. 3. Loading condition for the dead weight.

2.4.2 Design Pressure

The design pressure in the all secondary sodium side of IHX is set to 1.0 MPa. The pressure in the pipe generates the end cap load at the section of pipe. The end cap load at the secondary sodium pipes is calculated by 10.3 MPa and they are applied to the sections of two secondary sodium pipes as shown in Fig. 4.

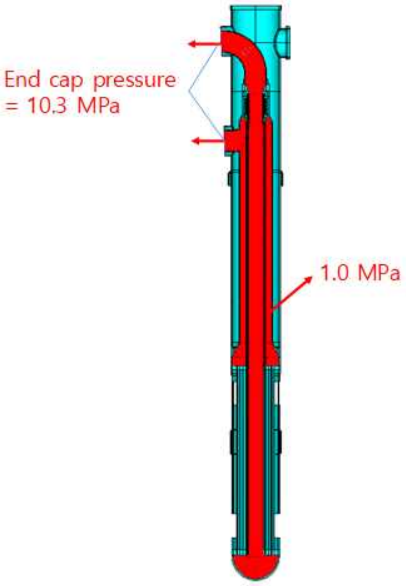


Fig. 4. Loading condition for the design pressure.

2.4.3 Secondary Sodium Weight

It is assumed that the dead weight of all secondary sodium in the inner pipe is applied at the lower chamber, and the dead weight of all secondary sodium above the upper tubesheet is applied at the upper surface of the upper tubesheet. Fig. 5 shows the equivalent pressures regarding the secondary sodium weights are applied at the lower chamber and upper tubesheet.

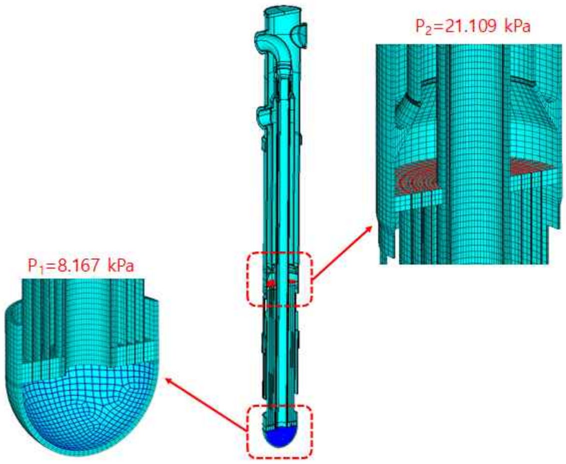


Fig. 5. Loading condition for the secondary sodium weight.

2.5 Analysis Results

2.5.1 Results of Structural Analyses

Fig. 6 shows the stress distributions for the dead weight of IHX. The maximum stress intensity that occurs at the Y-junction structure is 10.6 MPa and the maximum deflection is about 0.1 mm. Fig. 7 shows the stress distributions for the design pressure. The maximum stress intensity is 157 MPa and happens at the connection area between the upper tubesheet and IHX outer shell, and the maximum deflection is about 15.7 mm. Fig. 8. reveals the contours of stress intensity for the secondary sodium weight. The maximum stress intensity 1.14 MPa occurs at the Y-junction structure and the maximum deflection is about 0.01 mm.

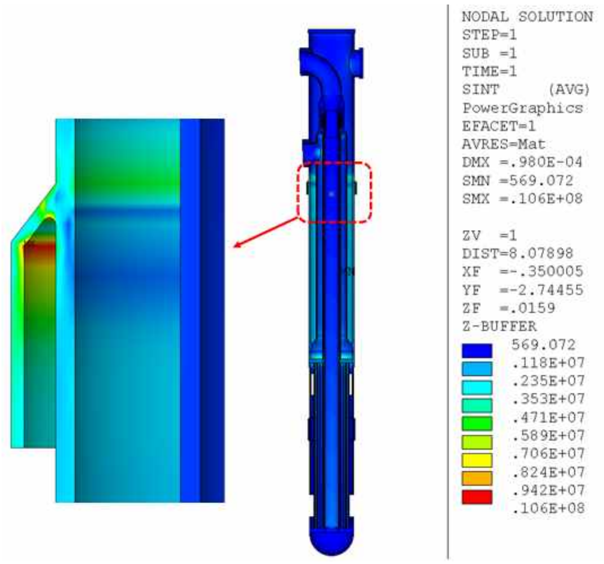


Fig. 6. Stress intensity distributions for the dead weight.

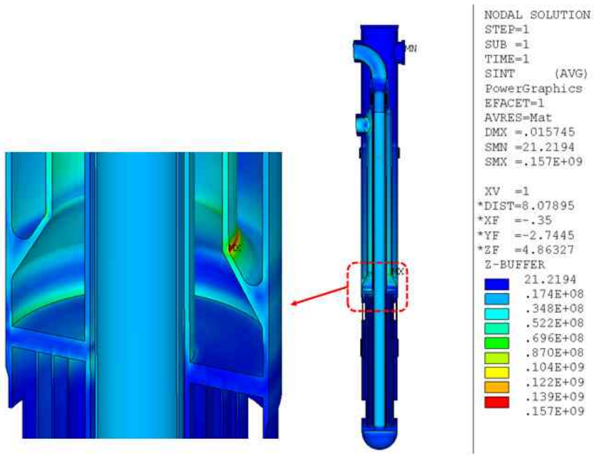


Fig. 7. Stress intensity distributions for the design pressure.

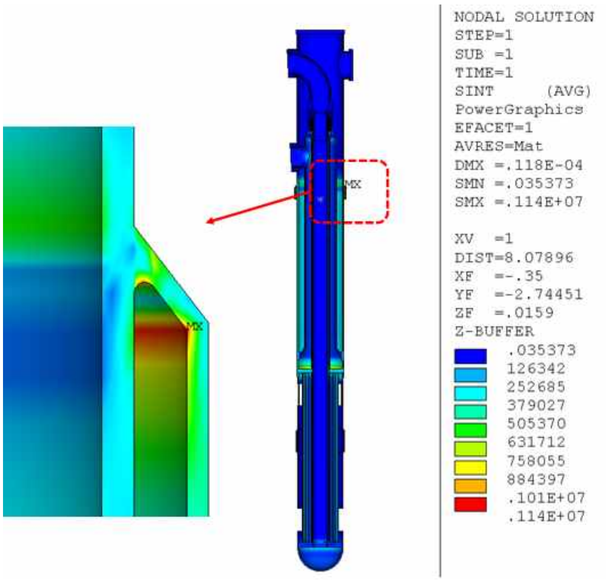


Fig. 8. Stress intensity distributions for the secondary sodium weight.

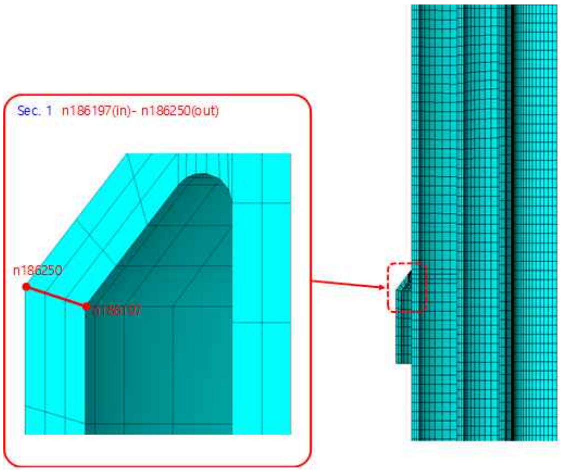
3. Structural Integrity Evaluations

Based on the results of structural analysis, the structural integrities of IHX have been evaluated using ASME BPV Sec. III Division 5 HB procedure.

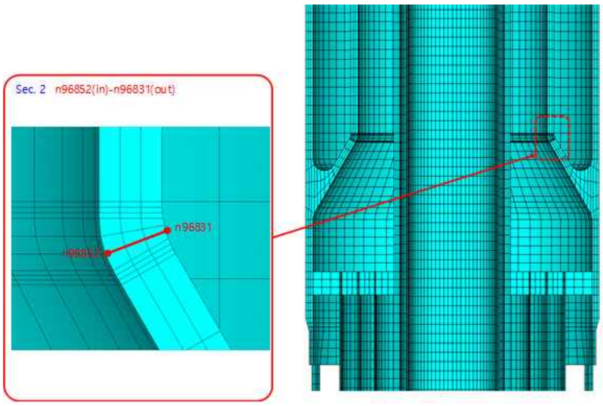
3.1 Evaluation Sections

In order to evaluate the structural integrity of IHX, the locations of stress concentration are chosen as an evaluation section. Fig. 9 shows the chosen evaluation sections, and their section information is as follows:

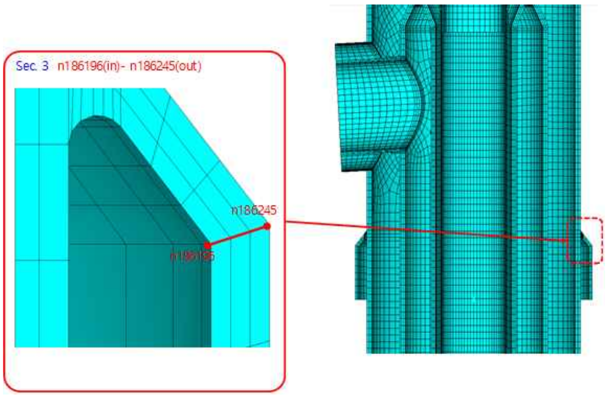
- Sec. 1: Y-junction structure #1, n186197-n186250.
- Sec. 2: Upper tubesheet, n96852-n96831.
- Sec. 3: Y-junction structure #2, n186196-n186254.
- Sec. 4: Hot secondary sodium outlet nozzle, n190252-n190504.



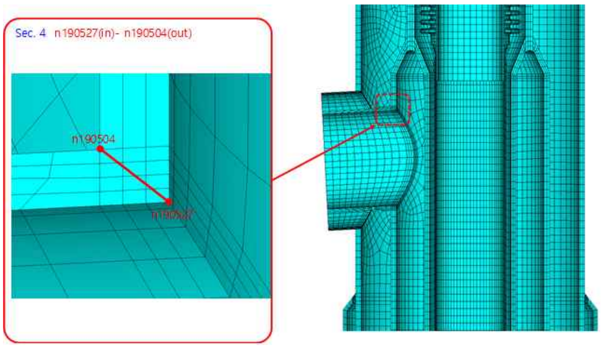
(a) Evaluation section (1)



(b) Evaluation section (2)



(c) Evaluation section (3)



(d) Evaluation section (4)

Fig. 9. Evaluation sections of IHX

3.2 Structural Integrity Evaluation

In order to evaluate stress integrity at each evaluation section, the stress linearization and load combinations are necessary. Table 1 shows the combined six stress tensors at the evaluation sections. On the basis of these calculated stresses, the structural integrities of evaluation sections are quantitatively calculated according to the ASME BPV Sec. III Division 5 procedure.

Table 2 shows the results of structural integrity for the design condition. The results of the section with the minimum design margin are as follows.

➢ Section-B, Outer(n96831), (temperature=520 ℃)
- Pm=64.07 MPa < So =120.2 MPa: satisfied. (design margin = 0.88)
- PL+Pb=136.8 MPa < 1.5So =180.3 MPa: satisfied. (design margin = 0.32)

The results reveal that all primary stresses in sections are satisfied with the design criteria for a design condition.

Table 1. Stress Linearization and Load Combination.

Sections	Nodes	Linearized Stress	Sx (Pa)	Sy (Pa)	Sz (Pa)	Sxy (Pa)	Syz (Pa)	Sxz (Pa)	Temperature (°C)
Section-1	Inner (186197)	Pm	1.93E+05	-4.68E+06	1.59E+06	-1.64E+06	1.38E+06	3.12E+05	520
		Pb	-2.66E+05	-5.25E+06	-8.78E+05	-1.59E+06	-5.30E+05	-1.98E+05	
		Pp	3.54E+05	-2.50E+05	3.82E+05	-1.75E+05	-1.54E+04	2.01E+04	
	Outer (186250)	Pm	1.93E+05	-4.68E+06	1.59E+06	-1.64E+06	1.38E+06	3.12E+05	520
		Pb	2.66E+05	5.25E+06	8.78E+05	1.59E+06	5.30E+05	1.98E+05	
		Pp	5.43E+04	-6.44E+05	-1.98E+05	-1.12E+05	-1.67E+04	1.08E+04	
Section-2	Inner (96852)	Pm	7.01E+07	4.11E+07	9.09E+06	1.33E+06	9.97E+06	-2.17E+06	520
		Pb	-1.72E+07	-8.57E+07	-5.45E+06	-7.59E+05	-2.90E+07	4.05E+05	
		Pp	1.66E+06	1.36E+07	-1.11E+06	1.04E+05	4.91E+06	-1.11E+04	
	Outer (96831)	Pm	7.01E+07	4.11E+07	9.09E+06	1.33E+06	9.97E+06	-2.17E+06	520
		Pb	1.72E+07	8.57E+07	5.45E+06	7.59E+05	2.90E+07	-4.05E+05	
		Pp	-8.92E+06	7.35E+06	-6.73E+06	1.05E+05	5.32E+06	1.56E+05	
Section-3	Inner (186196)	Pm	-2.39E+06	6.82E+06	-2.87E+05	7.21E+05	2.37E+06	1.59E+05	520
		Pb	1.34E+06	7.58E+06	3.71E+05	5.91E+04	2.31E+06	-1.86E+04	
		Pp	-5.55E+05	3.60E+05	-5.13E+05	4.19E+03	2.54E+05	5.15E+02	
	Outer (186245)	Pm	-2.39E+06	6.82E+06	-2.87E+05	7.21E+05	2.37E+06	1.59E+05	520
		Pb	-1.34E+06	-7.58E+06	-3.71E+05	-5.91E+04	-2.31E+06	1.86E+04	
		Pp	2.90E+05	9.32E+05	-7.80E+04	7.22E+01	1.63E+05	-9.45E+03	
Section-4	Inner (190527)	Pm	7.67E+07	3.09E+06	1.68E+06	-3.47E+06	-3.67E+06	-5.30E+06	520
		Pb	2.77E+07	-2.99E+06	9.07E+05	1.07E+06	3.57E+05	4.56E+05	
		Pp	-1.67E+06	-2.72E+06	-4.06E+06	2.44E+03	1.62E+06	5.01E+04	
	Outer (190504)	Pm	7.67E+07	3.09E+06	1.68E+06	-3.47E+06	-3.67E+06	-5.30E+06	520
		Pb	-2.77E+07	2.99E+06	-9.07E+05	-1.07E+06	-3.57E+05	-4.56E+05	
		Pp	-1.19E+06	-3.99E+06	-4.06E+06	3.18E+04	4.45E+06	-8.73E+04	

Table 2. Evaluation Results of Structural Integrity for Each Section under Design Condition.

Sections	Nodes	Linearized Stress	Calculated Stress (MPa)	Allowable Stress	Margin	Temperature (°C)	C&S
Section-1	Inner(186197)	Pm	7.34	So=120.20	15.38	520.0	ASME Sec III Div5-HBB
		PL + Pb	11.93	1.5So=180.30	14.11		
	Outer(186250)	Pm	7.34	So=120.20	15.38	520.0	ASME Sec III Div5-HBB
		PL + Pb	4.40	1.5So=180.30	39.98		
Section-2	Inner(96852)	Pm	64.07	So=120.20	0.88	520.0	ASME Sec III Div5-HBB
		PL + Pb	104.18	1.5So=180.30	0.73		
	Outer(96831)	Pm	64.07	So=120.20	0.88	520.0	ASME Sec III Div5-HBB
		PL + Pb	136.80	1.5So=180.30	0.32		
Section-3	Inner(186196)	Pm	10.04	So=120.20	10.97	520.0	ASME Sec III Div5-HBB
		PL + Pb	17.17	1.5So=180.30	9.50		
	Outer(186245)	Pm	10.04	So=120.20	10.97	520.0	ASME Sec III Div5-HBB
		PL + Pb	3.34	1.5So=180.30	52.98		
Section-4	Inner(190527)	Pm	79.07	So=120.20	0.52	520.0	ASME Sec III Div5-HBB
		PL + Pb	107.08	1.5So=180.30	0.68		
	Outer(190504)	Pm	79.07	So=120.20	0.52	520.0	ASME Sec III Div5-HBB
		PL + Pb	52.47	1.5So=180.30	2.44		

4. Conclusions

In this paper, the structural integrities of IHX under the design condition was quantitatively reviewed. It was confirmed that the structural integrities of IHX are satisfied with ASME BPV Sec. III Division 5 under a design condition. In the future, the structural integrities of IHX under a transient condition will also be reviewed.

Acknowledgement

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NOMENCLAURS

Pm: a primary membrane stress.
PL: a local membrane stress.
Pb: a primary bending stress.
So: the maximum allowable stress of general primary membrane stress intensity under design condition.

REFERENCES

[1] ASME BPV Sec. III Division 5.
[2] ANSYS Users manual, Release 18, ANSYS Inc.