Structural Integrity Evaluation of Intermediate Heat Exchanger for the Service Level-A Condition

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1. Introduction

The SALUS (Small, Advanced, Long-cycle and Ultimate Safe SFR) is a 100MWe SFR-based advanced power generation reactor with a long fuel cycle. To ensure its safe operation, the structural integrity of its various components, such as the intermediate heat exchangers (IHXs), must be evaluated under extreme operating conditions. The IHXs play a crucial role in transferring heat from the primary sodium to the secondary sodium. However, they are also subjected to high thermal loads, such as a temperature gradient between the primary and secondary coolants, which can cause thermal stresses and strains, leading to fatigue and creep failures during normal operation. Therefore, it is necessary to evaluate the structural integrity of the IHX under service level-A conditions.

This paper presents a comprehensive study of the structural integrity evaluation of the IHX under service level-A conditions in a sodium-cooled fast reactor. The study includes a structural and thermal stress analysis, as well as the results of the structural integrity evaluations, according to the ASME BPV Sec. III Division 5 Code [1].

2. Structural Analysis

The structural analysis of the IHX involves the evaluation of potential stresses, strains, and deformations that may occur due to mechanical loads during normal operation. The methodology and analysis model used in the previous study were described in [2]. In this section, the loading conditions for the service level-A condition are explained, and their analysis results are discussed.

2.1 Loading Conditions

The loading conditions refer to the applied external forces or pressures on a structure that affect its structural integrity. The primary loads subjected to the IHX in the service level-A condition are dead weight, operation pressure, and secondary sodium weight.

2.1.1 Dead Weight

The dead weight loading is a type of static load that is caused by the weight of the component itself and any other attached parts or components. In case of the IHX, the dead weight loading is caused by the weight of the heat exchanger tubes, support structures, and any other attached structures. Fig. 1 shows the loading condition of the dead weight. The acceleration due to gravity, which is approximately 9.8 m/s^2, is typically applied in the vertical direction of the IHX.

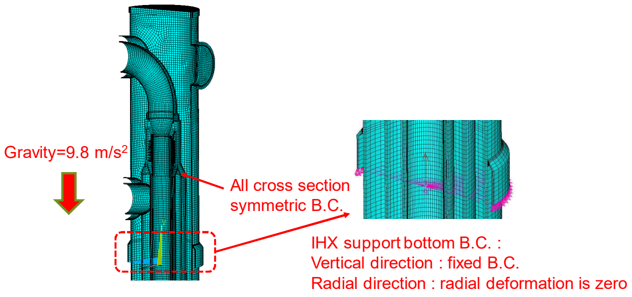


Fig. 1. Loading condition for the dead weight.

2.1.2 Operation Pressure

The operation pressure is an important parameter that needs to be considered during the structural integrity evaluation of the IHX. In this analysis, the operation pressure in the IHX is assumed to be 0.8 MPa conservatively. The end caps of the IHX are also subjected to significant loads due to the operation pressure. The end cap load is calculated based on the operation pressure and the load is applied in the form of uniformly distributed pressure acting on the end sections of two secondary sodium pipes as shown in Fig. 2.

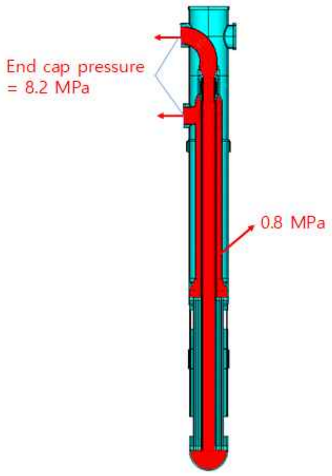


Fig. 2. Loading condition for the operation pressure

2.1.3 Secondary Sodium Weight

In addition to the dead weight, the IHX is subjected to the weight of the secondary sodium, which is another loading condition. The secondary sodium weight is caused by gravity acting on the sodium coolant that flows through the IHX. As shown in Fig. 3, the weight of all secondary sodium in the inner pipe is applied in the form of uniformly distributed pressure at the lower chamber, and the weight of all secondary sodium above upper tubesheet is applied in the form of uniformly distributed pressure at the upper surface of the inner tubesheet.

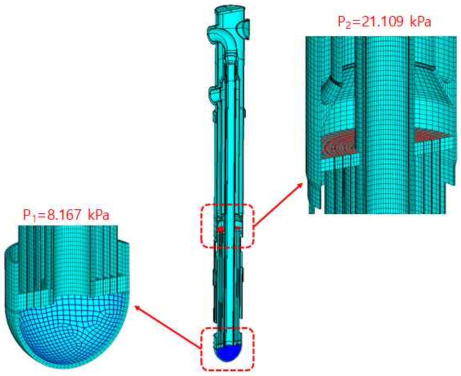


Fig. 3. Loading condition for the secondary sodium weight.

2.2 Analysis Results

The analysis results for the dead weight loading show that the maximum stress intensity that occurs at the Y-junction structure is 10.6 MPa, and the maximum deflection is about 0.1 mm, as shown in Fig. 4. For the operation pressure loading, the maximum stress intensity is 123 MPa and occurs at the connection area between the upper tubesheet and IHX outer shell, with the maximum deflection of about 12.3 mm, as shown in Fig. 5. For the secondary sodium weight loading, the maximum stress intensity of 1.14 MPa occurs at the Y-junction structure, and the maximum deflection is about 0.01 mm, as shown in Fig. 6.

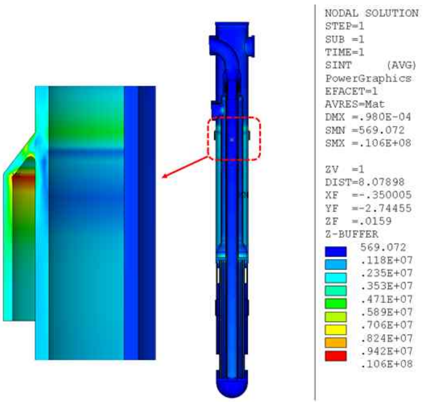


Fig. 4. Stress intensity distribution for the dead weight.

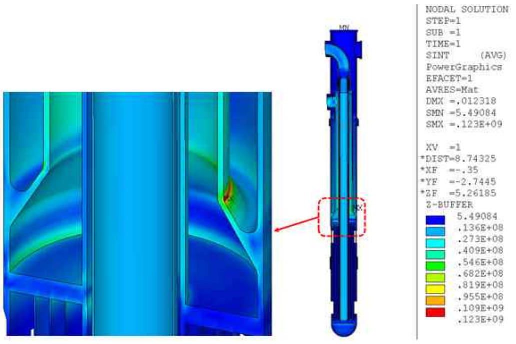


Fig. 5. Stress intensity distribution for the operation pressure.

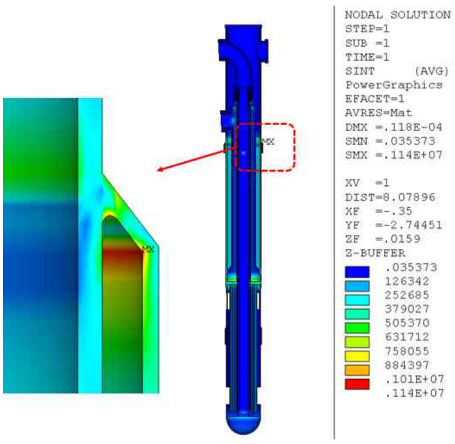


Fig. 6. Stress intensity distribution for the secondary sodium weight.

3. Thermal Analysis

This section outlines the assumptions and boundary conditions used for the IHX's thermal analysis, including the temperature distributions for each refueling condition and normal operation condition. It also includes the maximum thermal stress intensities during refueling and normal operation cycle.

3.1 Assumptions

The thermal analysis assumptions used in this study are as follows:

a. The heat transfer coefficient was assumed to be 10,000 W/℃·m² for the high speed liquid sodium flow region, 100 W/℃·m² for low speed liquid sodium flow region, and 3 W/℃·m² for the cover gas region.
b. The temperature of the cover gas region (region 5) was assumed to be 470℃, while the upper shielding structure region was assumed to vary linearly from 470℃ to 150℃ in the length direction.

c. The surface temperature of the reactor head at the Y-junction flange at the bottom of the IHX support was assumed to be 150℃.

d. The space between the reactor head lower casing and the secondary cylinder was assumed to be adiabatic.

e. The boundary condition of the surface between the internal piping of the IHX and the insulation shroud was assumed to be adiabatic due to the insulation material being filled.

f. The same structural boundary conditions used for the self-weight analysis were applied to calculate the thermal stress due to the thermal loads.

g. The duration time between the creep temperature (370℃) and the normal operation temperature (510℃) was conservatively assumed to be 40 hours.

3.2 Analysis Model

The analysis model used for the thermal analysis was based on the finite element method (FEM) using commercial software ANSYS [3]. The model for the thermal analysis consisted of a three-dimensional solid element SOLID70 with 8 nodes, and it included all the necessary geometric details of the IHX.

3.3 Thermal Boundary Conditions

The thermal boundary conditions for FEA model include the inlet and outlet temperatures of primary and secondary coolants, as well as the cover gas temperature. These conditions also take into account the heat transfer coefficients between coolants and walls of the tubes and the shell.

These temperature data used in the model were determined by performing a heat balance analysis that considers the operational characteristics of SALUS plant, and some data were established through conservative assumptions described in Section 3.1. The thermal boundary conditions of the IHX during the normal operation condition and refueling condition are presented in Fig. 7 and Fig. 8 respectively.

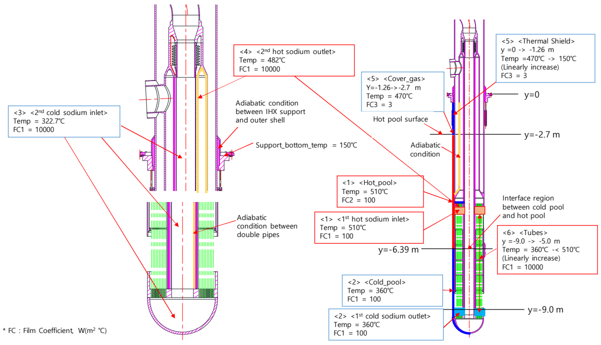


Fig. 7. Thermal boundary conditions for the normal operation condition.

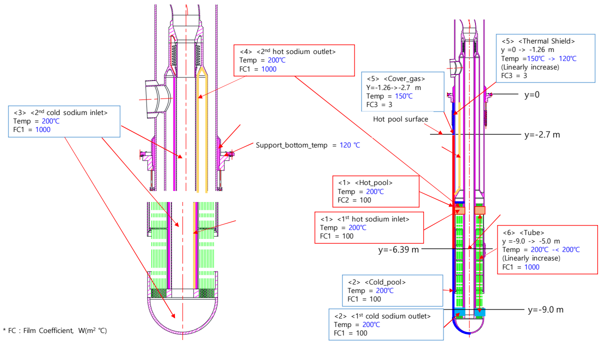


Fig. 8. Thermal boundary conditions for the refueling condition.

3.4 Analysis Results

3.4.1 Results of Thermal Analysis

Fig. 9 and Fig. 10 show the temperature and thermal stress intensity distributions across the IHX for the normal operation. The stress intensity is highest near the seal for separating the hot and sold sodium due to the temperature difference between the hot sodium and cold sodium. Fig. 11 and Fig. 12 also show the temperature and thermal stress intensity distributions for the refueling condition. The maximum stress intensity was founded at the same location but the maximum stress intensity was much lower than that for the normal operation condition.

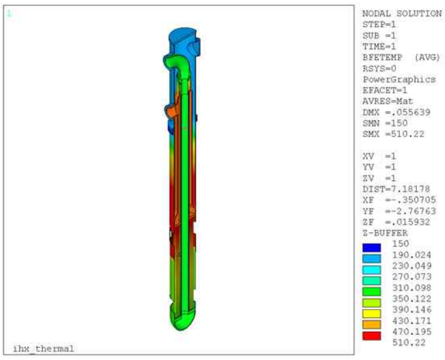


Fig. 9. Temperature distribution for the normal operation condition.

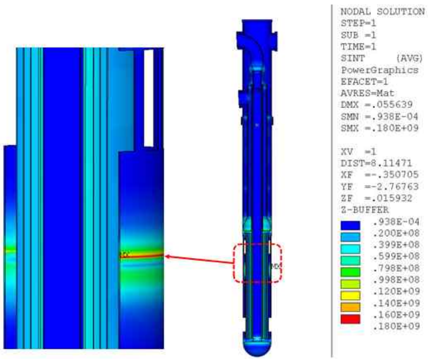


Fig. 10. Thermal stress intensity distributions for the normal operation condition

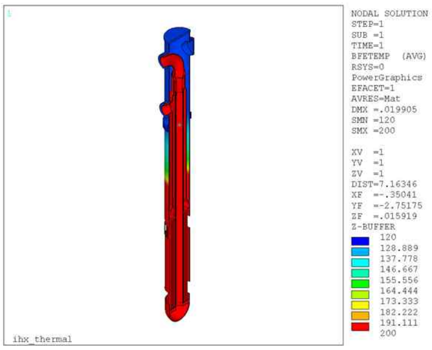


Fig. 11. Temperature distribution for the refueling condition.

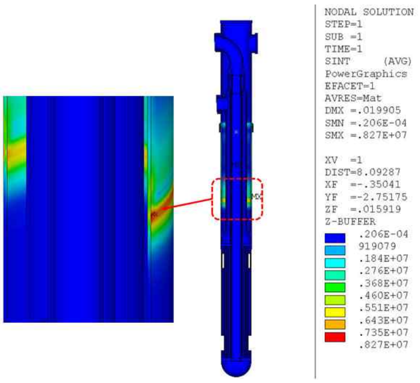


Fig. 12. Thermal stress intensity distributions for the refueling condition

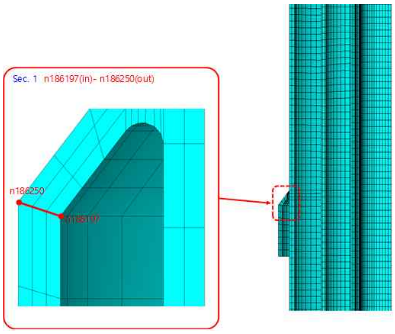
4. Structural Integrity Evaluations

The structural integrity evaluations are essential for ensuring the safety and reliability of components. In this study the structural integrity is evaluated based on the ASME BPV Section III Division 5 Code which provides guidelines and methods for performing structural integrity evaluations including stress, strain, fatigue, and creep analysis.

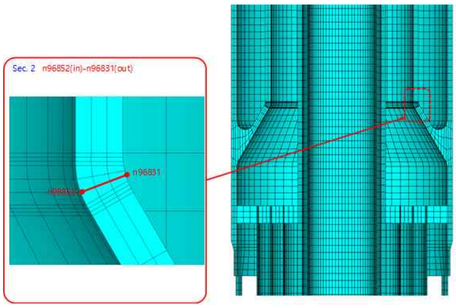
4.1 Evaluation Sections

In structural integrity evaluation, evaluation sections refer to specific areas or segments of the structure that are analyzed for their structural integrity. These selections are typically identified based on the factors such as presence of stress concentrations, locations of critical welds, or other factors could affect the overall structural integrity. In this study, the evaluation sections for the structural integrity evaluation of the IHX were selected based on the results of the structural and thermal analysis, Fig. 13 shows the chosen evaluation sections, and their section information is as follows:

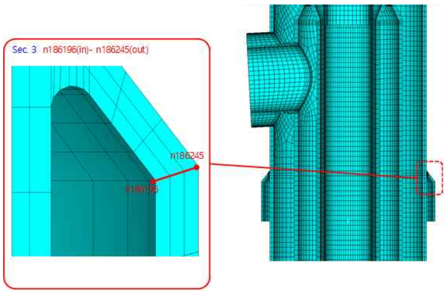
- Sec. 1: Y-junction structure #1, n186197-n186250.
- Sec. 2: Upper tubesheet, n96852-n96831.
- Sec. 3: Y-junction structure #2, n186196-n186254.
- Sec. 4: Hot secondary sodium outlet nozzle, n190252-n190504.
- Sec. 5: Seal, n13455-n10742.



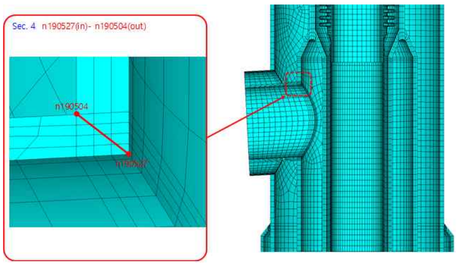
(a) Evaluation section (1)



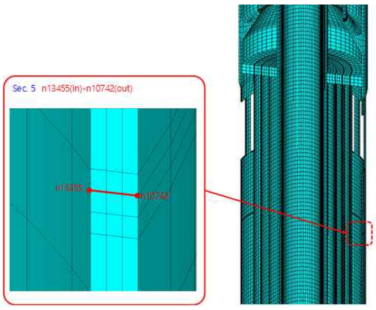
(b) Evaluation section (2)



(c) Evaluation section (3)



(d) Evaluation section (4)



(e) Evaluation section (5)

Fig. 13. Evaluation sections of IHX

4.2 Structural Integrity Evaluation

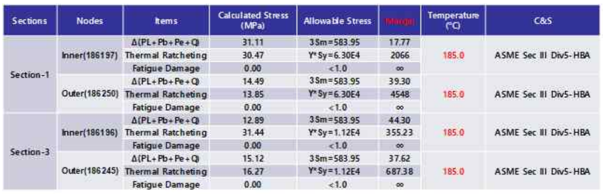
The ASME BPV Section III Division 5 Code provides the guidelines for evaluation of stress, and deformation and strain for the service level-A condition.

If the section temperatures are below the creep temperature, the maximum stress range, thermal ratcheting strain, fatigue damage shall be within the limits according to the HBA code, and if the section temperatures are above, the primary stress intensity, primary membrane plus bending stress intensities, inelastic strain, fatigue damage, and creep damage shall be within the limits specified in the HBB code.

Table 1 shows the results of the structural integrity evaluation at the evaluation sections which is below the creep temperature. The results reveal that all evaluation items are within the allowable limits specified in the ASME code.

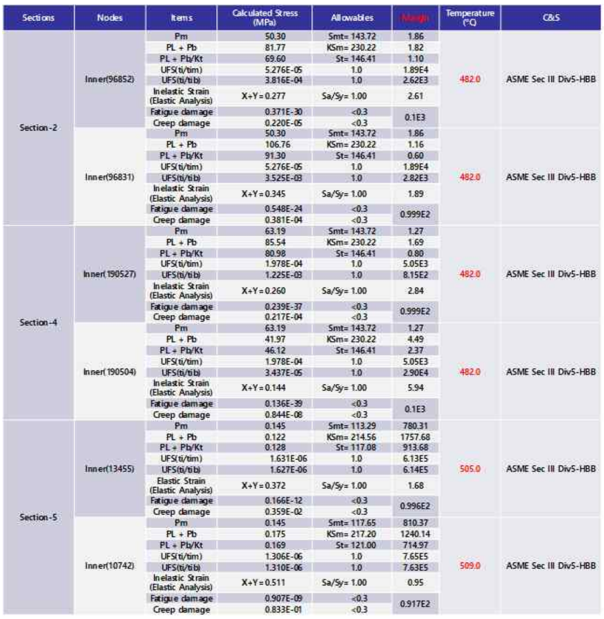
Table 2 shows the results of the structural integrity evaluation at the evaluation sections which is above the creep temperature. The impacts of creep and fatigue damages at all sections are negligible for the service level-A cycles during the entire design life. It is shown that the stresses and inelastic strains also have enough design margin at the all sections.

Table 1. Results of structural integrity evaluation for each section for service level-A (below creep temperature).



Sections	Nodes	Items	Calculated Stress (MPa)	Allowable Stress	Margin	Temperature (°C)	C&S
Section-1	Inner(186197)	Δ(PL+Pb+Pe+Q)	31.11	3Sm=583.95	17.77	185.0	ASME Sec III Div5-HBA
		Thermal Ratcheting	30.47	Y*Sy=6.30E4	2066		
		Fatigue Damage	0.00	<1.0	∞		
	Outer(186250)	Δ(PL+Pb+Pe+Q)	14.49	3Sm=583.95	39.30	185.0	ASME Sec III Div5-HBA
		Thermal Ratcheting	13.85	Y*Sy=6.30E4	4548		
		Fatigue Damage	0.00	<1.0	∞		
Section-3	Inner(186196)	Δ(PL+Pb+Pe+Q)	12.89	3Sm=583.95	44.30	185.0	ASME Sec III Div5-HBA
		Thermal Ratcheting	31.44	Y*Sy=1.12E4	355.23		
		Fatigue Damage	0.00	<1.0	∞		
	Outer(186245)	Δ(PL+Pb+Pe+Q)	15.12	3Sm=583.95	37.62	185.0	ASME Sec III Div5-HBA
		Thermal Ratcheting	16.27	Y*Sy=1.12E4	687.38		
		Fatigue Damage	0.00	<1.0	∞		

Table 2. Results of structural integrity evaluation for each section for service level-A (above creep temperature)



Sections	Nodes	Items	Calculated Stress (MPa)	Allowables	Margin	Temperature (°C)	C&S
Section-2	Inner(96852)	Pm	50.30	Smt= 143.72	1.86	482.0	ASME Sec III Div5-HBB
		PL + Pb	81.77	KSm= 230.22	1.82		
		PL + Pb/Kt	69.60	St= 146.41	1.10		
		UFS(ti/tim)	5.276E-05	1.0	1.89E4		
		UFS(ti/tib)	3.816E-04	1.0	2.62E3		
		Inelastic Strain (Elastic Analysis)	X+Y=0.277	Sa/Sy= 1.00	2.61		
		Fatigue damage	0.371E-30	<0.3	0.1E3		
		Creep damage	0.220E-05	<0.3			
	Inner(96831)	Pm	50.30	Smt= 143.72	1.86	482.0	ASME Sec III Div5-HBB
		PL + Pb	106.76	KSm= 230.22	1.16		
		PL + Pb/Kt	91.30	St= 146.41	0.60		
		UFS(ti/tim)	5.276E-05	1.0	1.89E4		
		UFS(ti/tib)	3.525E-03	1.0	2.82E3		
		Inelastic Strain (Elastic Analysis)	X+Y=0.345	Sa/Sy= 1.00	1.89		
		Fatigue damage	0.548E-24	<0.3	0.999E2		
		Creep damage	0.381E-04	<0.3			
Section-4	Inner(190527)	Pm	63.19	Smt= 143.72	1.27	482.0	ASME Sec III Div5-HBB
		PL + Pb	85.54	KSm= 230.22	1.69		
		PL + Pb/Kt	80.98	St= 146.41	0.80		
		UFS(ti/tim)	1.978E-04	1.0	5.05E3		
		UFS(ti/tib)	1.225E-03	1.0	8.15E2		
		Inelastic Strain (Elastic Analysis)	X+Y=0.260	Sa/Sy= 1.00	2.84		
		Fatigue damage	0.239E-37	<0.3	0.999E2		
		Creep damage	0.217E-04	<0.3			
	Inner(190504)	Pm	63.19	Smt= 143.72	1.27	482.0	ASME Sec III Div5-HBB
		PL + Pb	41.97	KSm= 230.22	4.49		
		PL + Pb/Kt	46.12	St= 146.41	2.37		
		UFS(ti/tim)	1.978E-04	1.0	5.05E3		
		UFS(ti/tib)	3.437E-05	1.0	2.90E4		
		Inelastic Strain (Elastic Analysis)	X+Y=0.144	Sa/Sy= 1.00	5.94		
		Fatigue damage	0.136E-39	<0.3	0.1E3		
		Creep damage	0.844E-08	<0.3			
Section-5	Inner(13455)	Pm	0.145	Smt= 113.29	780.31	505.0	ASME Sec III Div5-HBB
		PL + Pb	0.122	KSm= 214.56	1757.68		
		PL + Pb/Kt	0.128	St= 117.08	913.68		
		UFS(ti/tim)	1.631E-06	1.0	6.13E5		
		UFS(ti/tib)	1.627E-06	1.0	6.14E5		
		Elastic Strain (Elastic Analysis)	X+Y=0.372	Sa/Sy= 1.00	1.68		
		Fatigue damage	0.166E-12	<0.3	0.996E2		
		Creep damage	0.359E-02	<0.3			
	Inner(10742)	Pm	0.145	Smt= 117.65	810.37	509.0	ASME Sec III Div5-HBB
		PL + Pb	0.175	KSm= 217.20	1240.14		
		PL + Pb/Kt	0.169	St= 121.00	714.97		
		UFS(ti/tim)	1.306E-06	1.0	7.65E5		
		UFS(ti/tib)	1.310E-06	1.0	7.63E5		
		Inelastic Strain (Elastic Analysis)	X+Y=0.511	Sa/Sy= 1.00	0.95		
		Fatigue damage	0.907E-09	<0.3	0.917E2		
		Creep damage	0.833E-01	<0.3			

5. Conclusions

This paper presents the structural integrity evaluation of IHX for the service level-A conditions. The thermal analysis was performed by ANSYS software to determine the temperature distributions and thermal stresses under normal operation condition and refueling condition. The structural evaluation was then carried out based on the ASME BPV Sec. III Division 5 Code. The evaluation sections were selected based on their potential for high primary and secondary stresses. The stress, ratcheting, and fatigue damage were evaluated for the evaluation sections operating below the creep temperature, while the stress, inelastic strain, fatigue damage, and creep damage were evaluated for operation above the creep temperature. The evaluation results show that the IHX structure design meets the ASME BPV Sec. III Division 5 requirements for service level-A condition. In the future, further studies will be conducted to evaluate the structural integrity of IHX under transient conditions.

Acknowledgement

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NOMENCLAURS

Pm: primary membrane stress intensity.
PL: local membrane stress intensity.
Pb: primary bending stress intensity.
Pe: expansion stress intensity.
Q: thermal stress intensity.

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[2] S.K. Kim, and C.G. Park, Structural Integrity Evaluation of Intermediate Heat Exchanger under a Design Condition, Transactions of the Korean Nuclear Society Autumn Meeting, 2022.

[3] ANSYS users manual, Release 18, ANSYS Inc.