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Structural Integrity Evaluation of Intermediate Heat Exchanger in a Steady State Condition

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1. Introduction

In PGSFR (prototype Gen. IV sodium cooled fast reactor), 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.

The structural integrity of IHX is ensured by the choice of high ductile materials, and design and construction as per code like ASME. In order to respect the design code rule, the structural integrity evaluation of IHX was reviewed. In this study, the results of its structural integrities in a steady state condition based on ASME BPV Sec. III Division 5 HB[1] are addressed.

2. Structural and Thermal Analyses

In this section, the general assumptions and boundary conditions for the structural and thermal analyses are described. The analysis results include the maximum stress intensities and deflections for each loading condition under the design, service level A&B, and service level C conditions.

2.1 General Assumptions

The general assumptions for the structural and thermal analyses are as follows:

a. The temperature of primary inlet/outlet and secondary inlet/outlet is uniformly applied.
b. The temperature of tube bundle is linearly varied along axial direction and the temperature data of the IHX cylinder are imported from CFD analysis results.
c. Due to the temperature requirement of the reactor head, the thermal boundary condition of Y-junction structure is set to 150^{o}C.
d. It is assumed that thermal film coefficients at flow areas and at stagnation areas are 3,000W/^{o}C-m^2 and 10W/^{o}C-m^2, respectively.
e. Since a thermal insulation material is inserted into the annulus region between the IHX inner cylinder and thermal shield cylinder, it is assumed that their thermal boundary condition is considered as an adiabatic condition.
f. A 1/4 symmetric model is used for the structural and thermal analyses.
g. The secondary sodium weights at the lower chamber and upper tubesheet are applied as an equivalent pressure.
h. The effects of the static pressure for the primary and secondary sodium are ignored.
i. The buoyancy force of primary coolant and the primary and secondary sodium jet forces are ignored.

2.2 Analysis Model

Fig. 1 shows the geometric shape of IHX and its finite element model (FEM) made using ANSYS 15.0 [2]. A 1/4 symmetric model is used in the numerical simulations, and SOLID185 elements (8-node structural solid element) for structural analysis and SOLID 70 elements (8-node thermal solid element) for thermal analysis are used.

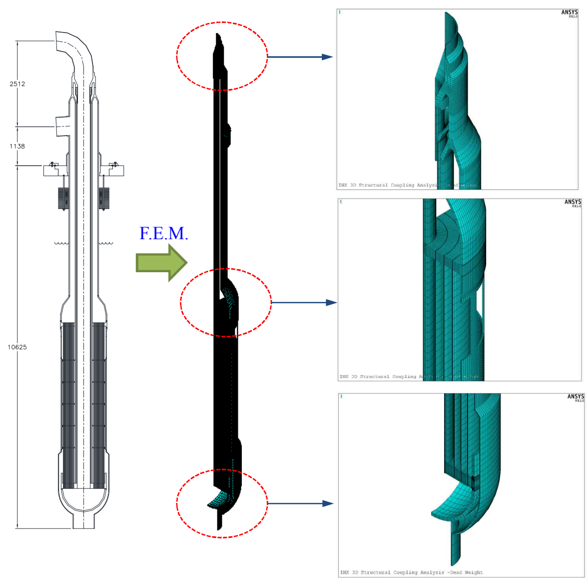

Fig. 1. 2D drawing of IHX and its finite element model.

2.3 Loading Conditions

During the normal operation, the primary loads (equals to mechanical loads) subjected to IHX are identified as its dead weight, design pressure, and secondary sodium weight. For the conservative analysis the dead weight of IHX is considered in an atmosphere temperature 21^{o}C condition. The design pressure in the secondary sodium side of IHX is set to 2.5 MPa by virtue of a sodium-water reaction pressure. The equivalent pressures regarding the secondary sodium weights are applied at the lower chamber and upper tubesheet. For the secondary loads (equals to thermal loads), temperature values in the full power operation are applied to relevant surfaces. Table 1 shows the load combinations for each service level.

2.4 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. In addition, since the finite element model is a 1/4 symmetric model, symmetric boundary conditions are also added.

Fig. 2 shows the temperature conditions in IHX. As shown in figure, the primary sodium inlet/outlet temperatures are applied to the upper/lower tubesheets and discharge structure, and the secondary sodium inlet/outlet temperatures are also applied to the inner cylinder and chamber. As mentioned in the general assumption, the thermal boundary condition of the IHX cylinder outer wall is set by mapping the temperature data generated from the CFD analysis.

Table 1. Load Combinations for Each Service Level.

Service Level	Event Name	Service Time (year)	No. of cycle	Max/Min Temp. (^{o}C)
Design Condition	- Dead weight - Design pressure - Secondary sodium weight	60	-	565
Level A&B	- Dead weight - Secondary sodium weight - Steady state full power operation	60	240	545/390
Level C	- Dead weight - Secondary sodium weight - Steady state full power operation - Sodium-water reaction pressure	60	25	545/390

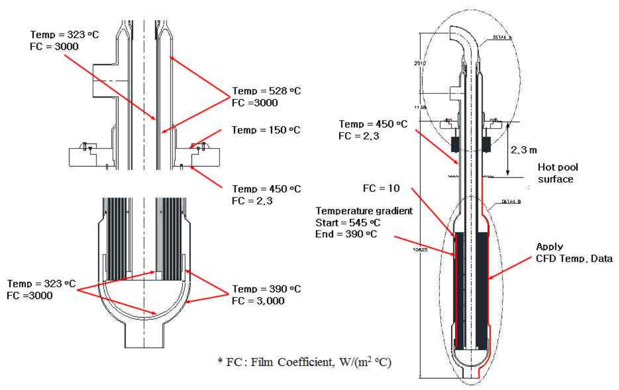

Fig. 2. Thermal boundary conditions.

2.5 Analysis Results

2.5.1 Results of Structural Analyses

Fig. 3 shows the stress distributions for the dead weight of IHX. The maximum stress intensity that occurs at the Y-junction structure is 11.9 MPa and the maximum deflection is about 0.1 mm. Fig. 4 shows the stress distributions for the design pressure. The maximum stress intensity is 167 MPa and happens at the connection area between the upper tubesheet and IHX outer shell. The maximum deflection is about 1.1 mm. Fig. 5 reveals the contours of stress intensity for the secondary sodium weight. The maximum stress intensity occurs at the Y-junction structure and the value is 2.4 MPa. The maximum deflection is about 0.02 mm.

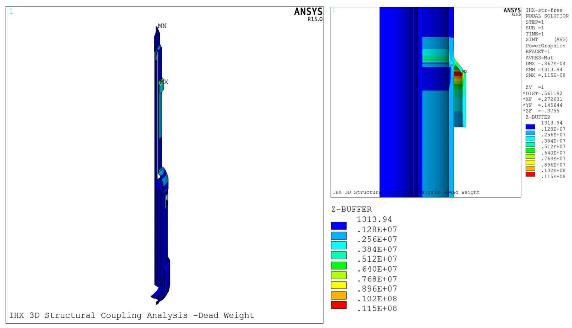

Fig. 3. Stress intensity distributions for the dead weight.

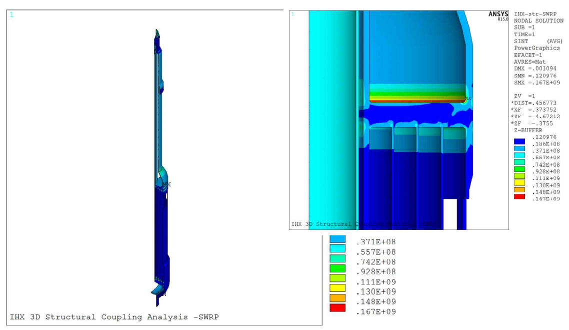

Fig. 4. Stress intensity distributions for the design pressure.

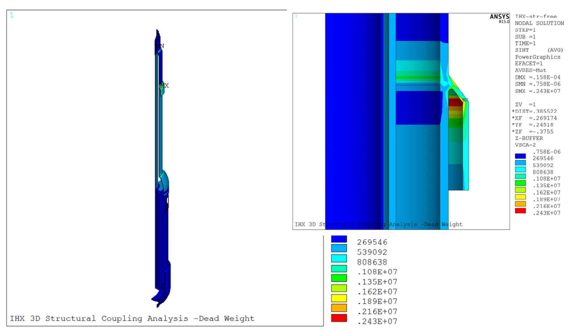

Fig. 5. Stress intensity distributions for secondary sodium weight.

2.5.2 Results of Temperature Distribution and Thermal Analyses

Fig. 6 shows the temperature distributions of IHX. As shown in figure, the maximum temperature is 545 ^{o}C in the IHX cylinder and a severe axial temperature gradient at the Y-junction structure is revealed. It results in the excessive thermal stress (420 MPa) as shown in Fig. 7, and this result is caused by the reactor head cooling requirement of 150°C.

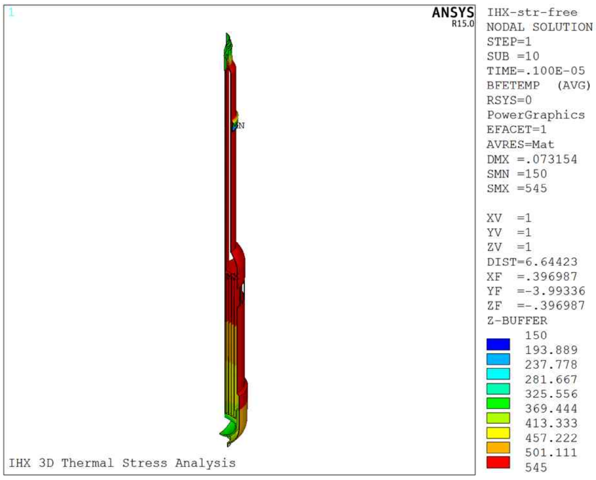

Fig. 6. Temperature distributions of IHX.

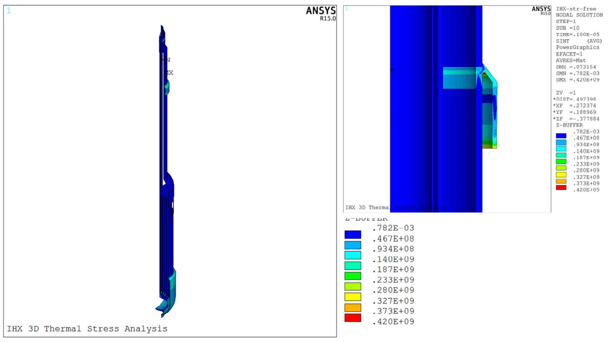

Fig. 7. Thermal stress distributions of IHX.

3. Structural Integrity Evaluations

Based on the results of structural and thermal analyses, the structural integrities of IHX have been evaluated using SIE-Div5 code [3], a computer program capable of the structural integrity evaluation by 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. 8 shows the chosen evaluation sections, and their section information is as follows:

- Section A: Y-junction structure #1, N279-N285.
- Section B: Y-junction structure #2, N2317-N2314.
- Section C: Upper chamber, N762-N761.
- Section D: Upper tubesheet, N402-N396.
- Section E: Lower chamber, N462-N453.

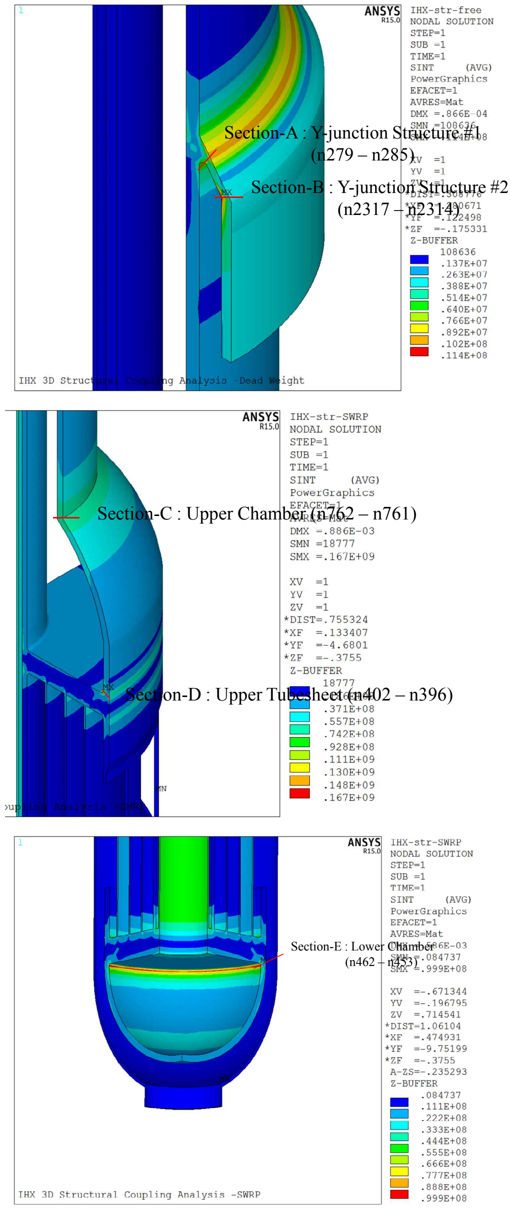

Fig. 8. Sections for structural integrity evaluations

3.2.1 Design Condition

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-D, Inner(402), (temperature=565 °C)
- Pm=32.71 MPa < So =89.40 MPa: satisfied, design margin = 1.73.
- PL+Pb=118.88 MPa < 1.5So =134.10 MPa: satisfied, design margin = 0.13.

The results reveal that all primary stresses in sections are satisfied with the design criteria for the design condition. However, it is shown that the section-D has an insufficient design margin.

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-A	Inner(279)	Pm	32.35	So= 89.40	1.76	565.0	ASME Sec III Div5-HBB
		PL + Pb	26.82	1.5So= 134.10	4.00		
	Outer(285)	Pm	32.35	So= 89.40	1.76	565.0	ASME Sec III Div5-HBB
		PL + Pb	39.56	1.5So= 134.10	2.39		
Section-B	Inner(2317)	Pm	39.46	So= 89.40	1.27	565.0	ASME Sec III Div5-HBB
		PL + Pb	56.44	1.5So= 134.10	1.38		
	Outer(2314)	Pm	39.46	So= 89.40	1.27	565.0	ASME Sec III Div5-HBB
		PL + Pb	26.08	1.5So= 134.10	4.14		
Section-C	Inner(762)	Pm	61.10	So= 89.40	0.46	565.0	ASME Sec III Div5-HBB
		PL + Pb	60.53	1.5So= 134.10	1.22		
	Outer(761)	Pm	61.10	So= 89.40	0.46	565.0	ASME Sec III Div5-HBB
		PL + Pb	61.67	1.5So= 134.10	1.17		
Section-D	Inner(402)	Pm	32.71	So= 89.40	1.73	565.0	ASME Sec III Div5-HBB
		PL + Pb	118.88	1.5So= 134.10	0.13		
	Outer(396)	Pm	32.71	So= 89.40	1.73	565.0	ASME Sec III Div5-HBB
		PL + Pb	81.18	1.5So= 134.10	0.65		
Section-E	Inner(462)	Pm	23.11	So= 89.40	2.87	565.0	ASME Sec III Div5-HBB
		PL + Pb	70.43	1.5So= 134.10	0.90		
	Outer(453)	Pm	23.11	So= 89.40	2.87	565.0	ASME Sec III Div5-HBB
		PL + Pb	40.62	1.5So= 134.10	2.30		

3.2.2 Service Level A&B

Table 3 shows the results of structural integrity for the service level A&B load combinations. The results of the section having the minimum design margin are as follows.

➢ Section-E, Inner(462), (temperature=344.6 °C)

- PL+Pb+Pe+Q=197.21 MPa < 3Sm =563.97 MPa: satisfied, design margin = 1.86.
- Thermal ratcheting =280.62 MPa < y*Sy =1.24E6 MPa: satisfied, design margin = 4416.

The results show that all primary and secondary stresses in sections are satisfied with the design criteria for the service level A&B load combinations.

Table 3. Evaluation Results of Structural Integrity for Each Section under Service Level A.

Sections	Nodes	Linearized Stress	Calculated Stress (MPa)	Allowable Stress	Margin	Temperature (°C)	C&S
Section-A	Inner(279)	Pm	6.94	Smt= 113.51	15.35	506.5	ASME Sec III Div5-HBB
		PL + Pb	8.00	KSm= 258.84	31.37		
		PL + Pb/Kt	7.39	St= 113.51	14.36		
		UFS(t/tm)	t= 525600	tm= 2713900	0.19		
		UFS(t/tb)	t= 525600	tb= 2704700	0.19		
	Outer(285)	Pm	6.94	Smt= 115.15	15.59	504.9	ASME Sec III Div5-HBB
		PL + Pb	10.44	KSm= 216.74	19.75		
		PL + Pb/Kt	9.53	St= 115.15	11.09		
		UFS(t/tm)	t= 525600	tm= 2730800	0.19		
		UFS(t/tb)	t= 525600	tb= 2678000	0.20		
Section-B	Inner(2317)	Pm	7.75	Smt= 204.84	25.42	430.2	ASME Sec III Div5-HBB
		PL + Pb	13.07	KSm= 307.26	22.52		
		PL + Pb/Kt	12.00	St= 208.33	16.37		
		UFS(t/tm)	t= 525600	tm= 3434200	0.15		
		UFS(t/tb)	t= 525600	tb= 3372700	0.16		
	Outer(2314)	Pm	7.75	Smt= 205.61	25.52	428.1	ASME Sec III Div5-HBB
		PL + Pb	3.95	KSm= 308.42	77.17		
		PL + Pb/Kt	4.18	St= 211.51	49.63		
		UFS(t/tm)	t= 525600	tm= 3462400	0.15		
		UFS(t/tb)	t= 525600	tb= 3514000	0.15		
Section-C	Inner(762)	Pm	2.47	Smt= 91.40	36.03	530.6	ASME Sec III Div5-HBB
		PL + Pb	1.33	KSm= 241.21	180.88		
		PL + Pb/Kt	1.40	St= 91.40	64.08		
		UFS(t/tm)	t= 525600	tm= 2552200	0.21		
		UFS(t/tb)	t= 525600	tb= 2576500	0.20		
	Outer(761)	Pm	2.47	Smt= 83.45	32.81	540.6	ASME Sec III Div5-HBB
		PL + Pb	4.05	KSm= 233.99	56.76		
		PL + Pb/Kt	3.73	St= 83.45	21.34		
		UFS(t/tm)	t= 525600	tm= 2459200	0.21		
		UFS(t/tb)	t= 525600	tb= 2429000	0.22		
Section-D	Inner(402)	Pm	1.15	Smt= 90.60	77.60	531.6	ASME Sec III Div5-HBB
		PL + Pb	2.40	KSm= 240.48	99.19		
		PL + Pb/Kt	2.15	St= 90.60	41.13		
		UFS(t/tm)	t= 525600	tm= 2573400	0.20		
		UFS(t/tb)	t= 525600	tb= 2550600	0.21		
	Outer(396)	Pm	1.15	Smt= 83.21	71.19	540.9	ASME Sec III Div5-HBB
		PL + Pb	0.79	KSm= 233.78	294.08		
		PL + Pb/Kt	0.64	St= 83.21	128.21		
		UFS(t/tm)	t= 525600	tm= 2487700	0.21		
		UFS(t/tb)	t= 525600	tb= 2499900	0.21		
Section-E	Inner(462)	PL + Pb + Pe + Q	197.21	3Sm= 563.97	1.86	344.6	ASME Sec III Div5-HBA
		Thermal Ratcheting	280.62	y*Sy= 1239546.65	4416.21		
	Outer(453)	Pm	0.13	Smt= 218.14	1652.45	382.7	ASME Sec III Div5-HBB
		PL + Pb	0.14	KSm= 327.21	2305.24		
		PL + Pb/Kt	0.10	St= 304.39	3095.29		
		UFS(t/tm)	t= 525600	tm= 13697000	0.04		
		UFS(t/tb)	t= 525600	tb= 13698000	0.04		

3.2.3 Service Level C

Table 4 shows the results of structural integrity for the service level C load combinations. The results of the section with the minimum design margin are as follows.

➢ Section-D, Inner(402), (temperature=531.6 °C)

- Pm=32.71 MPa < 1.2Sm =160.32 MPa: satisfied, design margin = 3.90.
- PL+Pb=81.18 MPa < K*Sm =233.78 MPa: satisfied, design margin = 1.88.
- PL+Pb/Kt=62.27 MPa < St=192.06 MPa: satisfied, design margin=2.08.
- tm=1,733,100 hours > ti=12.5 hours : satisfied.
- tbi=1,026,300 hours > ti=12.5 hours : satisfied.

The results show that all primary stresses in sections are satisfied with the design criteria for the service level C load combinations.

4. Conclusions

In this paper, the structural integrities of IHX under the design condition, service level A&B, and service level C load combinations have been reviewed. As a result, it was confirmed that the structural design of IHX is satisfied with ASME BPV Sec. III Division 5 under a steady state condition. In the future, the structural integrities of IHX under a transient condition will be reviewed.

Table 4. Evaluation Results of Structural Integrity for Each Section under Service Level C.

Sections	Nodes	Linearized Stress	Calculated Stress (MPa)	Allowable Stress	Margin	Temperature (°C)	C&S
Section-A	Inner(279)	Pm	32.35	1.2Sm= 172.56	4.33	506.5	ASME Sec III Div5-HBB
		PL + Pb	26.82	KSm= 258.84	8.65		
		PL + Pb/Kt	27.74	St= 238.15	7.59		
		UFS(t/tm)	t= 12.50	tm= 2192100	0.00		
		UFS(t/tb)	t= 12.50	tb= 2287000	0.00		
	Outer(285)	Pm	32.35	1.2Sm= 173.34	4.36	504.9	ASME Sec III Div5-HBB
		PL + Pb	39.56	KSm= 260.01	5.57		
		PL + Pb/Kt	38.03	St= 240.39	5.32		
		UFS(t/tm)	t= 12.50	tm= 2212400	0.00		
		UFS(t/tb)	t= 12.50	tb= 2096500	0.00		
Section-B	Inner(2317)	Pm	39.46	1.2Sm= 204.84	4.19	430.2	ASME Sec III Div5-HBB
		PL + Pb	56.44	KSm= 307.26	4.44		
		PL + Pb/Kt	53.02	St= 304.30	4.74		
		UFS(t/tm)	t= 12.50	tm= 2974400	0.00		
		UFS(t/tb)	t= 12.50	tb= 2777800	0.00		
	Outer(2314)	Pm	39.46	1.2Sm= 205.61	4.21	428.1	ASME Sec III Div5-HBB
		PL + Pb	26.08	KSm= 308.42	10.83		
		PL + Pb/Kt	27.53	St= 305.39	10.09		
		UFS(t/tm)	t= 12.50	tm= 3005400	0.00		
		UFS(t/tb)	t= 12.50	tb= 3177400	0.00		
Section-C	Inner(762)	Pm	61.10	1.2Sm= 160.81	1.63	530.6	ASME Sec III Div5-HBB
		PL + Pb	60.53	KSm= 241.21	2.99		
		PL + Pb/Kt	60.64	St= 205.14	2.38		
		UFS(t/tm)	t= 12.50	tm= 1216100	0.00		
		UFS(t/tb)	t= 12.50	tb= 1226500	0.00		
	Outer(761)	Pm	61.10	1.2Sm= 155.99	1.55	540.6	ASME Sec III Div5-HBB
		PL + Pb	61.67	KSm= 233.99	2.79		
		PL + Pb/Kt	61.56	St= 192.44	2.13		
		UFS(t/tm)	t= 12.50	tm= 1059300	0.00		
		UFS(t/tb)	t= 12.50	tb= 1048300	0.00		
Section-D	Inner(402)	Pm	32.71	1.2Sm= 160.32	3.90	531.6	ASME Sec III Div5-HBB
		PL + Pb	118.88	KSm= 240.48	1.02		
		PL + Pb/Kt	99.56	St= 203.87	1.05		
		UFS(t/tm)	t= 12.50	tm= 1850900	0.00		
		UFS(t/tb)	t= 12.50	tb= 320420	0.00		
	Outer(396)	Pm	32.71	1.2Sm= 155.85	3.76	540.9	ASME Sec III Div5-HBB
		PL + Pb	81.18	KSm= 233.78	1.88		
		PL + Pb/Kt	62.27	St= 192.06	2.08		
		UFS(t/tm)	t= 12.50	tm= 1733100	0.00		
		UFS(t/tb)	t= 12.50	tb= 1026300	0.00		
Section-E	Inner(462)	Pm	23.11	1.2Sm= 225.59	8.76	344.6	ASME Sec III Div5-HBA
		PL	23.11	1.8Sm= 338.38	13.64		
		PL+Pb	70.43	1.8Sm= 338.38	3.80		
	Outer(453)	Pm	23.11	1.2Sm= 218.14	8.44	382.7	ASME Sec III Div5-HBB
		PL + Pb	40.62	KSm= 327.21	7.06		
		PL + Pb/Kt	29.57	St= 322.54	9.91		
		UFS(t/tm)	t= 12.50	tm= 12702000	0.00		
		UFS(t/tb)	t= 12.50	tb= 12422000	0.00		

Acknowledgement

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NOMENCLAURS

Pm: a primary membrane stress.

PL: a local membrane stress.
Pb: a primary bending stress.
Pe: an expansion stress.
Q: a membrane+bending stress in the secondary stress.
So: the maximum allowable stress of general primary membrane stress intensity under design condition.
Sm: the lowest stress intensity at a given temperature.
Smt: the allowable limit of general membrane stress intensity to be used as a reference for stress calculation.
St: a temperature and time-dependent stress intensity limit.
Sy: a yield strength of a material at a given temperature.
y: the maximum allowable range of thermal stress.
K: the section factor for the cross section.
Kt: the factor given by Kt=(K+1)/2.
tm: the maximum allowed time under the load stress intensity.
ti: the total duration of a specific loading Pmi at elevated temperature.
tib: the time value determined by entering Figures NH-I-14.4A through NH-I-14.4E at a value stress equal to PL+Pb/Kt, as shown in Figure NH-3224-2[4].

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