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Structural Integrity Evaluation of Containment Vessel under Severe Accident for PGSFR

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1. Introduction

In case of PGSFR(Prototype Gen-IV Sodium Fast Reactor), the released heat from RV(Reactor Vessel) to outside is removed by RVCS(Reactor Vault Cooling System) using natural circulation air cooling. The purpose of RVCS is to maintain the integrity of concrete structure during normal power operation. Therefore RVCS should be designed to keep the temperature of concrete surface under design limit and to minimize heat loss through CV(Containment Vessel). And in case of severe accident, the integrity of reactor structure and concrete structure should be maintained. Therefore RVCS should be designed to satisfy ASME Level D service limits.

When RVCS works with breakdown of DHRS after severe accident, the temperature change of inner and outer surface of CV over time can affect structural integrity of CV. To verify the structural integrity, it is necessary to perform transient analysis of CV structure under changing temperature over time.

This paper provides structural integrity evaluation results of CV of the PGSFR(Prototype Gen-IV Sodium Fast Reactor) under severe accident through transient analysis. The evaluation was carried out according to ASME B&PV Code Sec. III-Subsection NH rule[1].

2. Finite element analysis

2.1 Geometry

The height and thickness of CV is 14.5m and 25mm, respectively. The shape of bottom head is torispherical type. And there are no penetration and attachment. The front view of CV is given in Fig. 1.

2.2 FE analysis

To perform FE(Finite Element) analysis of CV, 1/4 axisymmetric FE model of CV was modeled like Fig. 2(a). And 3-D expansion model of this axisymmetric model is shown in Fig. 2(b) for better understanding.

FE analysis was performed by using ANSYS 15.0 and PLANE183(8-Node Structural Plane element) and PLANE77(8-Node Thermal Plane element) were used for structural and thermal analysis, respectively[2].

When self-weight of CV was considered as load boundary condition, maximum stress was calculated as 1.56MPa at the connection point of cylinder and supporting flange as shown in Fig. 3. In case of applying leaked sodium coolant weight and hydrostatic pressure of leaked sodium coolant, maximum stresses were calculated as 0.38MPa and 61.5MPa at the connection point of bottom head and cylinder like Fig 4 and 5, respectively.

After severe accident, the temperature of inner and outer of CV changes over time like Fig. 6[3]. Thermal stress analysis was performed for this condition and maximum thermal stress was calculated as 16.29MPa (t=90437.9s) given in Fig. 7.

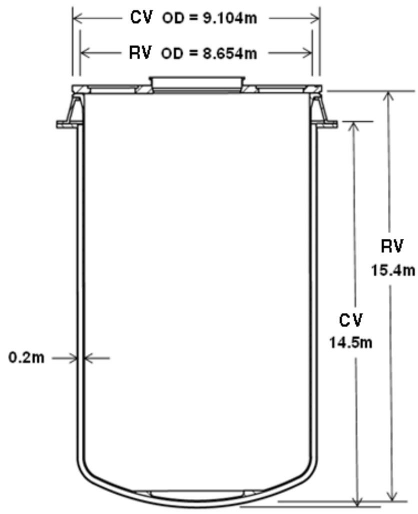
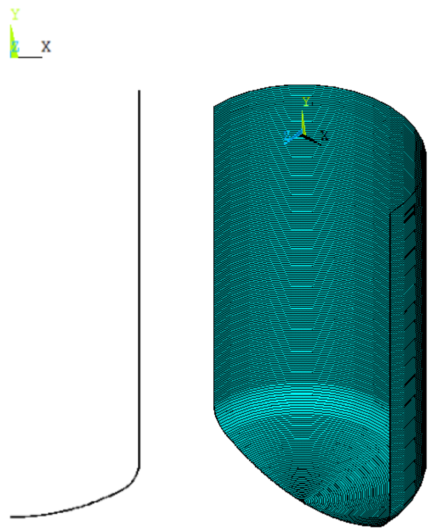


Fig. 1. Front view of the containment vessel.



(a) 1/4 axisymmetric model (b) expansion model
Fig. 2. FE model of containment vessel

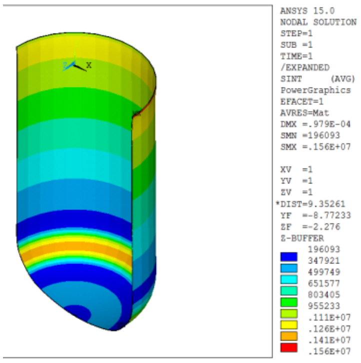


Fig. 3. Stress distribution of containment vessel by self-weight

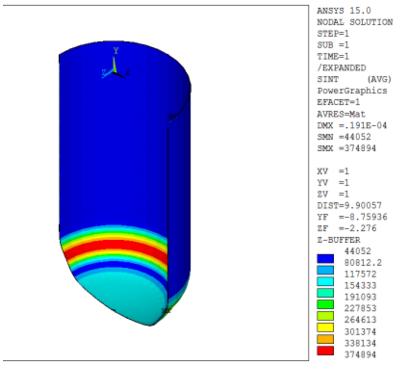


Fig. 4. Stress distribution of containment vessel by weight of leaked sodium coolant

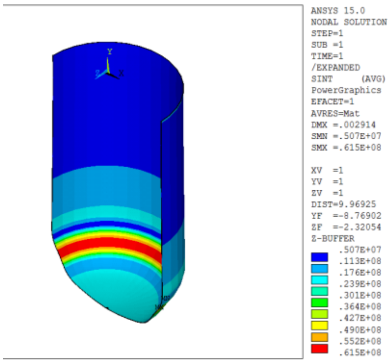


Fig. 5. Stress distribution of containment vessel by hydrostatic pressure of leaked sodium coolant

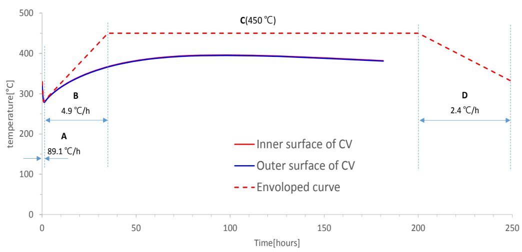


Fig. 6. Temperature changing curve of inner and outer of containment vessel over time after severe accident

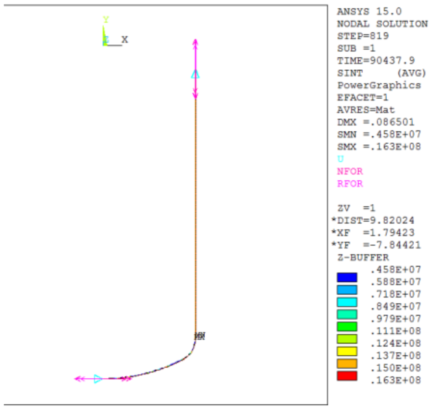


Fig. 7. Thermal stress intensity distribution of containment vessel (t=90437.9s)

3. Structural integrity evaluation

Structural integrity evaluation according to ASME NH rule was performed for 2 sections which were selected as high structural and thermal stress points like Fig. 8. For fast and accurate evaluation of structural integrity, SIE ASME-NH computer program was used.[4]

Linearized primary stresses for evaluation are given in Table 1. And linearized thermal stresses for upper extreme and lower extreme are also given in Table 2 and 3, respectively.

From the evaluation results given in Table 4, the minimum design margin which is defined in equation (1) is evaluated as 2.25.

$$\text{Design margin} = \frac{\textit{Allowable Stress}}{\textit{Calculated Stress}} - 1 \qquad (1)$$

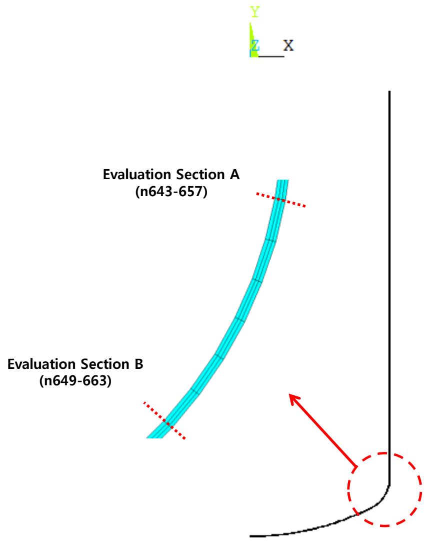


Fig. 8. Structural integrity evaluation sections

Table I: Linearized primary stress for severe accident

Sections	Nodes	Linearized Stress	Sx(Pa)	Sy(Pa)	Sz(Pa)	Sxy(Pa)	Temperature (℃)
Section-A	Inner (643)	Pm	-3.21E+05	1.14E+07	-1.94E+07	1.45E+06	450.0
		Pb	-1.73E+05	3.65E+06	7.77E+05	7.81E+05	
		Pp	-9.26E+04	-1.45E+05	-1.81E+05	-3.06E+04	
	Outer (657)	Pm	-3.21E+05	1.14E+07	-1.94E+07	1.45E+06	440.0
		Pb	1.73E+05	-3.65E+06	-7.77E+05	-7.81E+05	
		Pp	5.52E+04	2.01E+05	1.72E+05	-4.24E+03	
Section-B	Inner (649)	Pm	5.75E+06	8.46E+06	-3.73E+07	8.42E+06	450.0
		Pb	5.07E+06	6.24E+06	1.99E+06	6.53E+06	
		Pp	-3.84E+05	-3.62E+05	-5.64E+05	-1.05E+05	
	Outer (663)	Pm	5.75E+06	8.46E+06	-3.73E+07	8.42E+06	440.0
		Pb	-5.07E+06	-6.24E+06	-1.99E+06	-6.53E+06	
		Pp	3.72E+05	4.36E+05	5.33E+05	2.03E+05	

Table II: Linearized thermal stress for upper extreme

Sections	Nodes	Linearized Stress	Sx(Pa)	Sy(Pa)	Sz(Pa)	Sxy(Pa)	Temperature (℃)
Section-A	Inner (643)	Qm	-6.27E+04	-3.90E+03	0.00E+00	1.18E+04	400.4
		Qb	-5.57E+06	-1.53E+07	0.00E+00	-1.89E+06	
		Qp	-1.58E+06	-6.83E+05	0.00E+00	1.74E+05	
	Outer (657)	Qm	-6.27E+04	-3.90E+03	0.00E+00	1.18E+04	392.6
		Qb	5.57E+06	1.53E+07	0.00E+00	1.89E+06	
		Qp	1.34E+06	2.97E+05	0.00E+00	-2.03E+05	
Section-B	Inner (649)	Qm	-3.58E+04	-3.00E+04	0.00E+00	3.25E+04	400.4
		Qb	-9.96E+06	-1.09E+07	0.00E+00	-5.19E+06	
		Qp	-1.17E+06	-1.08E+06	0.00E+00	4.78E+05	
	Outer (663)	Qm	-3.58E+04	-3.00E+04	0.00E+00	3.25E+04	392.6
		Qb	9.96E+06	1.09E+07	0.00E+00	5.19E+06	
		Qp	8.71E+05	7.70E+05	0.00E+00	-5.57E+05	

Table III: Linearized thermal stress for lower extreme

Sections	Nodes	Linearized Stress	Sx(Pa)	Sy(Pa)	Sz(Pa)	Sxy(Pa)	Temperature (℃)
Section-A	Inner (643)	Qm	-5.80E+04	-3.62E+03	0.00E+00	1.09E+04	279.0
		Qb	-5.16E+06	-1.42E+07	0.00E+00	-1.75E+06	
		Qp	-9.40E+05	-2.76E+03	0.00E+00	1.82E+05	
	Outer (657)	Qm	-5.80E+04	-3.62E+03	0.00E+00	1.09E+04	271.3
		Qb	5.16E+06	1.42E+07	0.00E+00	1.75E+06	
		Qp	1.76E+06	8.99E+05	0.00E+00	-1.66E+05	
Section-B	Inner (649)	Qm	-3.32E+04	-2.78E+04	0.00E+00	3.01E+04	279.0
		Qb	-9.22E+06	-1.01E+07	0.00E+00	-4.81E+06	
		Qp	-5.15E+05	-4.24E+05	0.00E+00	5.01E+05	
	Outer (663)	Qm	-3.32E+04	-2.78E+04	0.00E+00	3.01E+04	271.3
		Qb	9.22E+06	1.01E+07	0.00E+00	4.81E+06	
		Qp	1.37E+06	1.29E+06	0.00E+00	-4.57E+05	

Table IV: Evaluation results for severe accident

Sections	Nodes	Linearized Stress	Calculated Stress (Mpa)	Allowable Stress (Mpa)	Margin	Temperature (℃)	C&S
Section-A	Inner (643)	Pm	3.10E+01	1.99E+02	5.41	450.0	ASME Sec Ⅲ Div5-HB Subpart B
		(PL + Pb/Kt)	3.34E+01	1.99E+02	4.95		
		UFS(ti/tir)	1.98E-04	1.00E+00	5044.92		
		UFS(ti/tibr)	2.05E-04	1.00E+00	4884.44		
	Outer (657)	Pm	3.10E+01	2.12E+02	5.84	440.0	ASME Sec Ⅲ Div5-HB Subpart B
		(PL + Pb/Kt)	2.86E+01	2.12E+02	6.41		
		UFS(ti/tir)	1.84E-04	1.00E+00	5421.41		
		UFS(ti/tibr)	1.79E-04	1.00E+00	5570.96		
Section-B	Inner (649)	Pm	5.29E+01	1.99E+02	2.75	450.0	ASME Sec Ⅲ Div5-HB Subpart B
		(PL + Pb/Kt)	6.11E+01	1.99E+02	2.25		
		UFS(ti/tir)	2.79E-04	1.00E+00	3581.18		
		UFS(ti/tibr)	3.29E-04	1.00E+00	3036.67		
	Outer (663)	Pm	5.29E+01	2.12E+02	3.00	440.0	ASME Sec Ⅲ Div5-HB Subpart B
		(PL + Pb/Kt)	4.48E+01	2.12E+02	3.73		
		UFS(ti/tir)	2.47E-04	1.00E+00	4049.06		
		UFS(ti/tibr)	2.19E-04	1.00E+00	4557.92		

4. Conclusions

Structural integrity of CV was evaluated through transient analysis of structure in case of severe accident. Stress evaluation results for selected evaluation sections satisfy design criteria of ASME B&PV Code Sec. III-Subsection NH. The transient load condition of normal operation will considered in the future work.

Acknowledgement

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[1] ASME B&PV Code Sec. III, Div. 1-Subsection NH, Class1 components in Elevated Temperature Service, ASME, 2013.
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