Transaction of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, May 29-30, 2008

Review of the Structural Integrity for a VHTR Cooled Vessel Concept

Jong-Bum Kim, Dong-Ok Kim, Keun-Bae Park, Won-Jae Lee
Korea Atomic Energy Research Institute, 150 Dukjin-dong Yuseong-gu, Daejeon, Korea, jbkim@kaeri.re.kr

1. Introduction

The objective of this study is to evaluate the structural integrity of the RPV for a proposed cooled vessel design which adopts SA533 Grade B, Class 1 as a RPV material. The RPV temperature during a normal operation is maintained below 371℃ so that the ASME Code, Section III, Subsection NB[1] is applicable for this evaluation. Two thermal transient conditions (HPCC and LPCC) initiated from the four normal operating conditions were considered in the evaluation of the structural integrity as the accident conditions. When the RPV temperature exceeds 371 ℃ during thermal transients, the Code Case N-499-1(CC N-499)[2] shall be used to evaluate the structural integrity. The CC N-499 describes general guidelines and allows the ASME Code Section III, Subsection NH[3] as an applicable design code.

2. Modeling and Analysis

In order to evaluate the structural integrity of the cooled vessel, the RPV is modeled and the thermo-mechanical analyses are conducted using the ANSYS finite element code[4]. The schematic of the RPV model is shown in Fig. 1. The height, inner diameter, and thickness of the RPV are 24,083mm, 7,660mm, and 190mm, respectively.

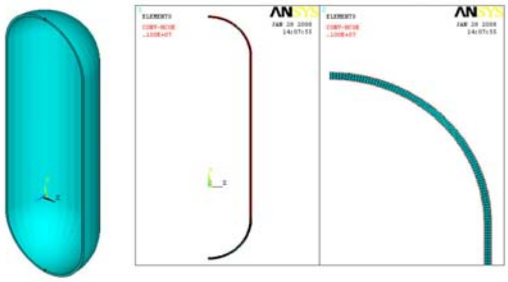


Fig. 1 Finite Element Model of the RPV

During a normal operation, the pressure inside the RPV is assumed as 7MPa and the inlet/outlet gas temperatures are assumed either 490℃/950℃ or 590℃/950℃. By the combination of two gas temperature cases and two RCCS types, total of four normal operation cases are considered. The two accidents considered in these analyses are the HPCC (High Pressure Conduction Cooldown) and the LPCC (Low Pressure Conduction Cooldown) initiated at the four normal operations. Total of eight cases of transient conditions are considered as shown in Table 1, whose thermal transient loadings are provided by the GAMMA+ analyses[5, 6] and their pressure loadings are assumed to be constant of 7MPa for the conservatism of the structural analysis. Support loads, nozzle loads, flange loads as well as seismic loads are not considered at this conceptual design stage.

Table 1. Transient cases and characteristics

Case No	1	2	3	4	5	6	7	8
Inlet /Outlet	490℃/950℃				590℃/950℃			
RCCS type	Air cooled		Water cooled		Air cooled		Water cooled	
Transient type	HPCC	LPCC	HPCC	LPCC	HPCC	LPCC	HPCC	LPCC

3. Structural Integrity Assessment

3.1 Normal operating conditions

The structural analyses with thermo-mechanical loadings have been performed for the four normal operating conditions corresponding to the cases given in Table 2. The temperatures of the RPV remain below 371℃ at all locations as expected. Membrane stress intensities (P_m) are dominant and they satisfy the allowable stress limit (S_m). The combined primary and secondary stress intensities (P_L+P_b+Q) satisfy the allowable stress limit ($3S_m$) as shown in Table 2.

Table 2. Design margins – steady state conditions

Case	T_{mean} (℃)	P_m (MPa)	P_L+P_b (MPa)	P_L+P_b+Q (MPa)	S_m (MPa)	Margin	
1&2	327.9	145	151	180	184	0.3	2.1
3&4	301.8	145	151	181	184	0.3	2.0
5&6	338.2	145	151	178	184	0.3	2.1
7&8	334.4	145	151	192	184	0.3	1.9

Temperature profile along the RPV at the normal operations of Cases 1&2 and the corresponding stress intensity distribution are shown in Fig. 2. This is typical throughout all the cases considered.

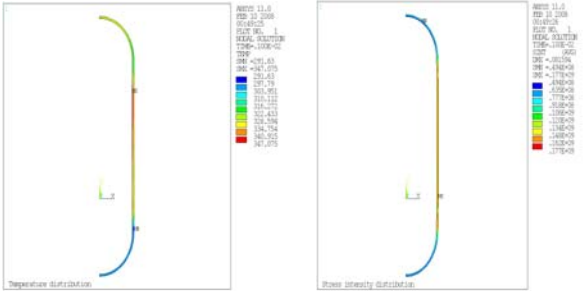
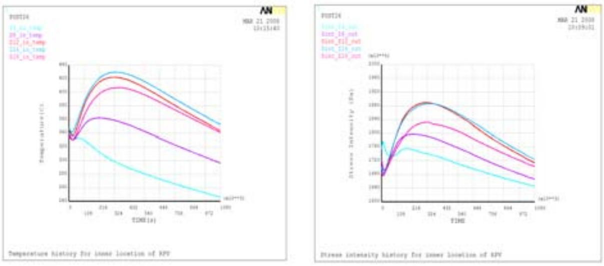


Fig. 2 Temperature(Left) and Stress Intensity(Right) distributions for the Cases 1&2

3.2 Accident conditions

The structural transient analyses have been performed for eight transient cases. Temperature histories along the inner surface at the selected elevations are shown in Fig. 3(a) and the stress intensities are as shown in Fig. 3(b) for Case 1.



(a) Inner Temperatures (b) Outer Stress Intensities

Fig. 3 Temperature and stress intensity histories for Case 1

At elevated temperatures above 371℃, P_L+0.8P_b should be smaller than the time dependent stress intensity S_t. Table 3 shows that the design is adequate for all the cases at this conceptual stage, even though Cases 2 and 6 show relatively small design margins due to the high temperatures. It is noteworthy that the value of S_t decreases rapidly as the temperature increases and the limiting transient cases are Cases 2 and 6 for the LPCC accident condition with an air cooled RCCS.

Table 3. Design margins – transient conditions

Case No	P_L+0.8P_b(MPa)	S_t(MPa)	T_{max_i}(℃)	Margin
1	150	300	429.7	1.0
2	150	193	518.9	0.3
3	150	358	379.0	1.4
4	150	310	459.0	1.1
5	150	318	435.1	1.1
6	150	180	524.9	0.2
7	150	358	383.9	1.4
8	150	300	464.4	1.0

The maximum accumulated inelastic strain limits should be satisfied in regions expecting elevated temperatures. An effective creep stress σ_c is determined by Subsection NH procedures. In the evaluation of the creep-fatigue damage, the number of occurrences of each transient is assumed as one, and the isochronous curves of the CC N-499 were used to obtain the total creep strain ($\Delta\varepsilon_c$). Negligible amount of inelastic strains were calculated for the cases except for Case 2 and Case 6. The inelastic strains for Cases 2 and 6 are 0.04% and 0.05% respectively, which are far below the allowable limit, 1%.

The allowable number of allowable cycles (N_d) is determined by applying the total strain ranges (ε_t) into the design fatigue curve. The minimum stress-to-rupture time (T_r) is determined by applying a stress level S_j. Fatigue damage (D_f) is the ratio of the number of transient occurrences over the allowable number of cycles, and the creep damage (D_c) is the ratio of the time duration over the stress rupture time.

The effect of the creep-fatigue interaction is determined using the curve shown in Fig. 4 in which the region under the bi-linear curve indicates a safe area. It is shown that the results for all cases are in the safe area. Creep damage for Case 6 turned out to be noticeable and the other values are negligibly small.

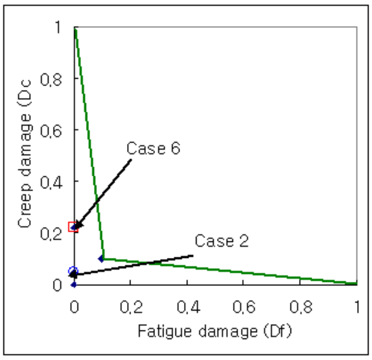


Fig. 4 Creep-fatigue damages

4. Conclusions and Discussion

The structural integrity of a cooled vessel, whose material is SA533 Grade B, Class 1, against both normal operating conditions and transient thermal loadings has been demonstrated per the ASME Code Subsection NB, CC N-499 and Subsection NH.

It should be noted that the discussion so far is based on a simplified vessel configuration without nozzles, flanges, or supports. Also, seismic events are to be considered for detailed assessments later.

ACKNOWLEDGMENT

This study was supported by the Korean Ministry of Education, Science and Technology through its National Nuclear Technology Program.

REFERENCES

[1] ASME Section III, Subsection NB, Class 1 Components, 2004

[2] ASME Section III, Code Case N499-2, Use of SA-533 Grade B, Class 1 Plate and SA-508 Class 3 Forgings and Their Weldments for Limited Elevated Temperature Service, 2004

[3] ASME Section III, Subsection NH, Class 1 Components in Elevated Temperature Service, 2004

[4] ANSYS Release 11.0, ANSYS Inc., 2006

[5] H.S. Lim, H.C. No, "GAMMA Multi-dimensional Multi-component Mixture Analysis to Predict Air Ingress Phenomena in an HTGR," Nuclear Science and Engineering, Vol. 152, pp. 87-97, 2006

[6] Kim, M. H., "Thermal Fluid and Safety Analyses of a Preliminary Cooled-Vessel Design for NHDD Plant", Calc. Note, NHDD-KA-07-RD-CD-001, KAERI, 2007.