

Study on the Long-Term Passive Cooling Extension of AP1000 Reactor Postprint

Authors: Ye Cheng, ZHENG Mingguang, WANG Yong, QIU Zhongming

Date: 2023-06-18T00:00:00+00:00

Abstract

The AP1000 is a Generation III pressurized water reactor (PWR) characterized by high safety, with its passive safety system representing a significant design feature. However, its passive cooling capability can only be sustained for 72 h and requires additional support from either on-site or off-site sources. To address this limitation, the present study employed the WGOOTHIC software to calculate and analyze the water inventory in the passive containment cooling water tank under various conditions. The results demonstrate that with a cooling water inventory of 6553.78 m³, AP1000 nuclear power plants can achieve long-term, completely passive cooling without requiring any external support. Similar outcomes are achieved when a 65-mm-thick containment wall increases the design pressure rating to 0.6 MPa with a cooling water inventory of 5673 m³. Furthermore, the AP1000 shield building was correspondingly modified. An ANSYS analysis of the structural stability of the shield building with a 6000 m³ cooling water inventory confirmed that the new design satisfies both seismic design requirements and safe residual heat removal requirements for large-scale PWRs.

Full Text

Preamble

Nuclear Science and Techniques 24 (2013) 040601

Study on the Long-Term Passive Cooling Extension of AP1000 Reactor

YE Cheng^{1,2,*} ZHENG Mingguang² WANG Yong^{2,3} QIU Zhongming^{1,2}

¹School of Nuclear Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

²Shanghai Nuclear Engineering Research and Design Institute, Shanghai

200233, China

³Zhejiang University, Hangzhou 310058, China

Abstract

The AP1000 is a Generation III pressurized water reactor (PWR) with high safety features, most notably its passive safety systems. However, its passive cooling capability is limited to 72 hours and requires additional support from either inside or outside the plant. To address this limitation, this study employs WGOETHIC software to calculate and analyze the water inventory in the passive containment cooling water tank under various conditions. The results demonstrate that when the cooling water inventory is 6553.78 m³, AP1000 nuclear power plants can achieve long-term, completely passive cooling without any internal or external support. Similar outcomes are achieved when a 65-mm-thick containment wall increases the design pressure rating to 0.6 MPa(g) with a cooling water inventory of 5673 m³. Corresponding improvements to the AP1000 shield building were also made. ANSYS analysis of the structural stability of the shield building with a 6000 m³ cooling water inventory confirmed that the new design meets seismic design requirements and the safe residual heat removal requirements of a large-scale PWR.

Key words: Passive cooling, Passive containment cooling system, WGOETHIC

Introduction

The AP1000 system is a third-generation, large-scale, advanced passive pressurized water reactor (PWR) developed by Westinghouse. It features a single-heap layout of two-loop units with 1250 MW electric power and a 60-year design life. Its safety system incorporates a completely passive design [?, ?]. The passive containment cooling system (PCS) is one of the most critical passive safety systems, and its reliability and heat dissipation performance are directly related to the safety of nuclear power plants (NPPs). Passive design significantly improves the safety performance of the AP1000 and enhances its market competitiveness. Sutharshan et al. [?] and Schulz [?] have described the Westinghouse PCS in detail.

The PCS system is shown in Fig. 1. During an accident, when the internal pressure of the containment reaches the H-2 setpoint, the isolation valve of the tank automatically opens, deploying passive containment cooling. Consequently, evaporation of the cooling water sprayed onto the containment forms a heat sink and dissipates excess heat away from the reactor.

Currently, the AP1000 PCS tank (PCCWST) is designed for a water inventory of 3000 m³, which is adequate for 72 hours of spraying, after which active water replenishment from the passive containment cooling auxiliary tank becomes necessary. The PCS cooling water in the water tank plays a crucial role in reactor safety. After 72 hours of PCCWST spray, operator intervention becomes necessary because the passive heat sink is no longer available. Heat dissipates from

the reactor core to the containment through the continuous evaporation and condensation of the internal working fluid. In the AP1000, containment cooling effectively corresponds to core cooling during long-term cooling scenarios.

In this study, we first analyze the PCCWST water inventory and the containment wall thickness in the AP1000 PCS, then propose design improvements for the AP1000 shield building based on these calculations. Finally, ANSYS is applied to analyze and verify the new design structure, leading to a proposal for a large-scale, completely passive PWR cooling method.

2.1 WGOOTHIC System Modeling and Input Conditions

The WGOOTHIC program is used for safety analysis of the AP1000 containment model nodes, as shown in Fig. 2. Andreani et al. [?] have conducted numerous GOTHIC application studies. The CLIME module, added by Westinghouse specifically for the PCS system, simulates the steam condensation process from the inside, heat transfer of the inner water film, wall heat conduction, heat transfer of the outer water film, water film evaporation, and radiation heat transfer between different walls.

The conditions of the WGOOTHIC containment model include continuous break flow, droplets, and the pressure, enthalpy, and flow changes over time of the vapor component, steam flow after activating the ADS4 valve, IRWST injection flow, and pit injection flow. The initial conditions include node initial pressure, temperature, relative humidity, initial water inventory, and gas partial pressure. The program parameters control the time step in the accident calculation and the result outputs.

In the AP1000 containment, the mass and energy releases are greater in a double-ended guillotine break of the hot leg than in the double-ended guillotine break of the cold leg (DECLG) accident. In the long-term phase, the DECLG accident releases stored energy from equipment, including steam generators. Therefore, a large fracture in a cold leg represents the worst-case scenario. This paper uses the DECLG accident as the subject case. The ANS79 formula is used to calculate the AP1000 core decay heat for 3400 MW thermal power. The WGOOTHIC input data are calculated by Relap5 (Fig. 3).

2.2 Results and Discussion

As shown by the gauge pressure curve (a) in Fig. 4, when there is no water in the PCCWST, the containment pressure rises after the accident and exceeds the containment design pressure (0.407 MPa(g)) at 1000 s. Subsequently, the pressure further increases and reaches a peak pressure of 2 MPa(g) at 305,217 s (3.5 days), while the shell temperature reaches 213°C. The air-cooling capability of the containment increases with temperature. At this point, the decay heat is 14 MW, and the core decay heat and air-cooling capacity reach equilibrium. Therefore, the containment temperature and pressure gradually decrease over

time. If the containment has sufficient pressure capacity, fully passive core cooling can be achieved without cooling water in the PCCWST. However, from a practical engineering perspective, it is difficult for a large pressure vessel with a free volume of $5.83 \times 10^4 \text{ m}^3$ to achieve this condition.

The pressure curve in Fig. 4(b) shows that when the AP1000 NPP is not supplied with cooling water after 72 hours in a timely manner, the containment pressure rises quickly. After 341,242 s (4 days), the containment pressure exceeds the safe containment design pressure of 0.407 MPa(g). At 717,245 s (8.3 days), the containment pressure reaches a peak pressure of 1.18 MPa(g), and the maximum temperature rises to 186°C. However, if cooling water is supplied before the containment design pressure is exceeded, the accident can be resolved, ensuring the containment remains undamaged. Otherwise, there is a high probability of overpressure rupture, potentially leading to the release of radioactivity.

The pressure curve (c) in Fig. 4 shows that if the AP1000 NPP PCCWST is equipped with cooling water for 1,696,000 s (19.6 days) (when no cooling water is supplied thereafter), the containment pressure will reach the safe containment design pressure at 1,790,000 s (20.7 days) and the highest pressure of 0.56 MPa(g) at 2,290,000 s (26.5 days). The highest temperature reached is 153°C with approximately 5673 m³ of cooling water. Although the containment pressure exceeds the design pressure, the AP1000 containment yield limit pressure is approximately 0.6 MPa(g), indicating a high probability that the containment will remain intact.

The pressure curve (d) in Fig. 4 shows that when the cooling-water inventory in the AP1000 NPP PCCWST maintains for 30 days (when no cooling water is supplied thereafter), the maximum containment pressure reaches 0.403 MPa(g), and the maximum temperature reaches 141°C. Under these conditions, the decay heat equals the air cooling capability. The containment pressure and temperature slowly decrease over time, and the air cooling capacity always matches the decay heat. After 30 days, the core decay heat is less than 6 MW, and the containment maintains a relatively high pressure and temperature. In cases where the pressure is lower than the design pressure, the containment itself has an air cooling capacity that is adequate for dissipating the decay heat.

The temperature curves in Fig. 4B show the temperature variation of the containment. Because the containment becomes saturated after the accident, the temperature and pressure curves converge.

Fig. 4 shows long-term containment pressure and temperature curves for different cases: (A) Gauge pressure, (B) Temperature. For PCCWST conditions: (a) Without water, (b) 72-h water amount loaded, (c) 19-d water amount loaded, (d) 30-d water amount loaded.

Table 1 lists the limiting cases and PCCWST water amounts for each working condition. It can be seen that an appropriate increase in the amount of PCCWST water can fulfill the conditions for fully passive cooling.

Table 1 The limits of different cases

Case	Peak pressure / MPa(g)	Peak temperature / °C	Cooling water / m ³
No cooling water after accident	2.0	213	0
Cooling water inventory for 72 h	1.18	186	3000
Cooling water inventory for 20 h	0.56	153	5673
Cooling water inventory for 30 h	0.403	141	6553.78

3 Containment-Wall Thickness Analysis

In assessing the containment, the effect of wall thickness on the final containment pressure and temperature was analyzed using the WGOthic model with 6-MW decay-heat long-term cooling, with no PCCWST cooling water and a core decay heat of 6 MW for three different typical wall thicknesses.

The pressure curves corresponding to different thicknesses are notably similar. This result shows that differences in wall thickness have little influence on the peak pressure of the containment, indicating that changes in thermal resistance caused by thickness variations have minimal effect on overall heat transfer.

Fig. 5 shows the pressure and temperature curves of the containment for three different wall thicknesses. The temperature trend shows similar characteristics. The WGOthic-calculated values are shown in Table 2.

Table 2 Comparison of AP1000 pressures and different containment thicknesses

Wall thickness / mm	Maximum pressure / Pa(g)	Design pressure / MPa(g)
44.4*	0.403	0.407
50	0.403	0.45
65	0.403	0.6

*AP1000 design thickness

The containment design pressure varies significantly with wall thickness, but the peak pressure remains relatively stable. This effect is mainly observed because the design pressure increases with thickness, although the containment thermal resistance only accounts for a small portion of the total thermal resistance.

The ASME Section III Volume NE-3324.3 formula [?] for a cylinder with minimum allowable thickness is adopted for the wall-thickness calculation of the AP1000 containment as follows:

$$t = \frac{PR}{SE - 0.6P}$$

Where P is the design pressure, R is the radius of the safety containment, and S is the yield stress. For SA-738 B-grade material for AP1000, the maximum yield stress is 184.1 MPa. Because the wall thickness of the cylinder is greater than that of the cylinder end, which constitutes a dominant factor in heat transfer, we use the cylinder-wall thickness. Following ASME requirements, when the cylinder-wall thickness is 65 mm, the design pressure of the containment is 0.6 MPa(g).

4 Design Verification and Structure Improvements

Because of the constant evaporation and condensation of the AP1000 safety-containment internal working fluid, heat dissipates from the core to the containment. Containment cooling is equivalent to core cooling in long-term cooling scenarios. To ensure that this air-cooling method can fully dissipate the decay heat of the core and that the pressure does not exceed the design pressure of the containment when all cooling water is exhausted, the passive containment cooling water inventory, the PCS air cooling capacity, the shield building design, and the containment design pressure must be increased.

Various design options are available. In this paper, the current AP1000 design is improved to achieve a fully passive cooling effect. The adopted method does not increase the diameter of the shield building but expands the PCCWST tank diameter and increases the containment wall thickness to improve the design pressure of the containment. The PCCWST water inventory is increased to 6000 tons, and the wall thickness of the containment is increased to 65 mm. Fig. 6 and Table 3 compare the dimensions of the new PCCWST with the original AP1000.

The overall structural stability of the nuclear island is analyzed using a finite element numerical model. In the original AP1000 design, the PCCWST stores 3000 m³ of cooling water to guarantee fulfillment of the 72-hour cooling requirement. In the new design, the corresponding PCCWST size is enlarged. Additionally, the containment-wall thickness of the shield building is increased in consideration of the possibility of aircraft collision. The corresponding finite element model is shown in Fig. 7(a). The PCCWST changes are shown in Fig. 7(b). In the new design, taking into account the actual distribution of water in the tank, 35% of the water mass is distributed uniformly onto the bottom of the tank, as shown in Fig. 7(c).

Table 3 Comparison of the dimensions of the new and original schemes

Schemes	Water tank / m ³	Nuclear island mass / t	Shield	R1 / mm	R2 / mm	R3 / mm	H1 / mm	H2 / mm	H3 / mm
			building thickness / mm						
Original	3000	1.28	44	-	-	-	-	-	-
New	6000	1.28	65	-	-	-	-	-	-

	Water tank / Schemes ³	Nuclear island mass / t	Shield building thickness / mm	R1 / mm	R2 / mm	R3 / mm	H1 / mm	H2 / mm	H3 / mm
New	6000	1.35×10^5	55	-	-	-	-	-	-

The finite element model uses hard rock as a foundation. The overall mass of the nuclear island increases more in the new design than in the original design due to the additional water and enlarged concrete components. To stabilize the nuclear island in the new design, static calculations under dead-load and live-load conditions have been conducted, and the response spectrum as a function of SSE seismic loads has been analyzed.

The analysis of the response spectrum follows the design guidelines of the U.S. NRC RG 1.92 [?] and applies combination method B to the modal response combination. The CQC method is used for the periodic modal response combination, the Der Kiureghian coefficient is used to calculate the oscillation-mode self-correlation coefficient, the stiffness response combinations are calculated using algebraic sums, the cyclical component and the stiffness component of the modal response are separated by the Lindley-Yow method, and the stiffness response is calculated using the static ZPA method. The seismic spatial components in three directions (NS, EW, and VT) are combined by the SRSS method. The calculated base seismic forces are shown in Table 4.

Table 4 Seismic shear and vertical force on the basement

Seismic response	EW shear / $\times 10^5$ kN	NS shear / $\times 10^5$ kN	VT reaction / $\times 10^5$ kN
Original	-	-	-
New	-	-	-

The stability of the nuclear island on the hard rock foundation was assessed using the above results. The calculation takes into account the impact of active earth pressure and passive earth pressure. The three safety factors for anti-floating, anti-slip, and anti-overturning are shown in Table 5.

Table 5 Results of the safety factor calculation

Design	Anti-floating safety factor	Anti-slip safety factor	Anti-overturning safety factor
		Axis 1	Axis 11
Original	3.70	-	-
New	-	-	-

The axis positions in Table 5 are shown in Fig. 8. All three safety factors meet the original AP1000 civil structure design criteria. Therefore, the air cooling can dissipate the core decay heat. The new shield building analysis using ANSYS shows that the new design meets seismic requirements.

5 Conclusion

Long-term and completely passive cooling can be achieved without operator intervention, even for a large-scale PWR, but an ultimate air heat sink is required. Because the containment provides a relatively large ultimate air heat sink, this AP1000 reactor can achieve completely passive cooling without the 72-hour limit when the core power, containment, and shield building are reasonably matched. In this paper, the PCCWST tank diameter and water inventory are increased to 6000 m³, the containment wall thickness is increased to 65 mm, and the containment design pressure is increased to 0.6 MPa(g). Because the water inventory in the PCCWST tank is sufficient for 20 days of spray, at which point the decay heat is 7 MW, the containment pressure remains less than the design pressure.

References

1. Zhang J, Liu F, Huang L. Nucl Sci Tech, 2011, 22: 73 76.
2. Alrwashdeh M, Yu G L, Wang K. Nucl Sci Tech, 2011, 311: 566 575.
3. Sutharshan B, Mutyala M, Vijuk R P, et al. Energy Procedia, 2011, 7: 293 302.
4. Schulz T L. Nucl Eng Des, 2006, 236: 1547 1557.
5. Andreani M, Kapulla R, Zboray R. Nucl Eng Des, 2012, 249: 71 81.
6. Andreani M, Paladino M, George T. Nucl Eng Des, 2010, 240: 1528 1547.
7. Chen Y S, Yuann Y R, Dai L C. Nucl Eng Des, 2012, 247: 106 115.
8. Papini D, Grgic D, Cammi A, et al. Nucl Eng Des, 2011, 241: 1152 1164.
9. Prabhudharwadkar D M, Iyer K N, Mohan N, et al. Nucl Eng Des, 2011, 241: 832 842.
10. Sawant P, Khatib-Rahbar M. Nucl Eng Des, 2011, 241: 3824 3838.
11. American Society of Mechanical Engineers. Section III, Division 1, Class MC Components, ASME, New York.
12. United States Nuclear Regulatory Commission. RG 1.92 Rev.2: Combining modal responses and spatial components in seismic response analysis, NRC, Maryland.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.