Study on the long-term passive cooling extension of AP1000 reactor

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Abstract The AP1000 with high safety is a generation III pressurized water reactor (PWR), its significant feature is passive safety system. However, its passive cooling can only maintain for 72 h and requires additional support from inside or outside the plant. To solve this problem, this study utilized the WGOTHIC software to calculate and analyze the water inventory in the passive containment cooling water tank under different conditions. The results show that when the cooling water inventory is 6553.78 m^3, the AP1000 nuclear power plants can achieve long-term, completely passive cooling without any inside or outside the plant. The same outcomes occur when 65-mm-thick containment wall increases the design pressure rating to 0.6 MPa at the cooling water inventory of 5673 m^3. Also, the AP1000 shield building was accordingly improved. An ANSYS analysis of the structural stability of the shield building with a 6000 m^3 cooling water inventory confirmed that the new design can meet the requirements of the seismic design and the safe residual heat removal requirements of a large-scale PWR.

Key words Passive cooling, Passive containment cooling system, WGOTHIC

1 Introduction

The AP1000 system, which is a third-generation, large -scale, and advanced passive pressurized water reactor (PWR) developed by US Westinghouse, consists of a single heap layout of two-loop units with 1250 MW electric power and a design life of 60 years. Its safety system is in line with a completely passive design[1,2]. The passive containment cooling system (PCS) is one of the most important passive safety systems, and its reliability and thermal dissipating performance are directly related to the safety of nuclear power plants (NPPs). Passive design can significantly improve the safety performance of the AP1000, and increase its competitiveness in the market. Sutharshan *et al.*[3] and Schulz[4] have described the Westinghouse PCS in detail.

The PCS system is shown in Fig.1. In the event of an accident, when the internal pressure of the containment reaches H-2, the isolation valve of the passive containment cooling tank automatically deploys. Consequently, evaporation of the cooling water sprayed onto the containment forms a heat trap and dissipates overheat away from reactor.

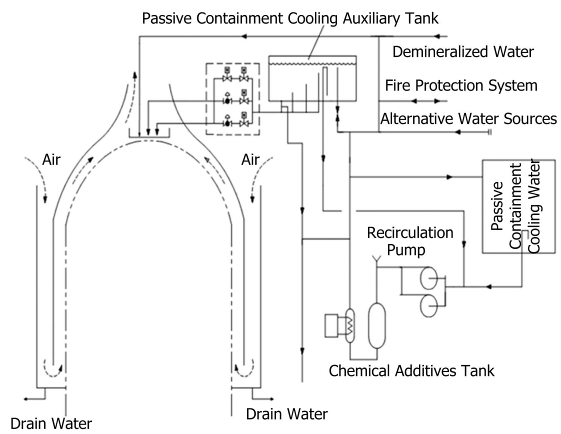

Fig.1 AP1000 PCS schematic diagram.

Currently, the AP1000 PCS tank (PCCWST) designed for a water inventory of 3000 m^3 is adequate for 72 h spraying, and active water is replenished from the passive containment cooling auxiliary tank. Therefore, the PCS cooling water in the water tank

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plays an important role in the reactor's safety. After the 72 h PCCWST spray, the operator intervention becomes necessary because the passive heat sink is no longer available.

The heat dissipates from the reactor core to the containment because the continuous evaporation and condensation of the internal working fluid in the AP1000, containment cooling actually corresponds to core cooling. In this study, first the PCCWST water inventory and the wall thickness of the containment in the AP1000 PCS, and design improvements based on these calculations are proposed for the AP1000 shield building. Finally, ANSYS is applied to analyze and verify the new design structure, and a large-scale, completely passive PWR cooling method is proposed.

2 PCCWST water inventory optimization

2.1 WGOTHIC system modeling and input conditions

The WGOTHIC program is used for the safety analysis of the AP1000 containment model nodes, as shown in Fig.2.

Andreani *et al.*[5-10] have conducted numerous GOTHIC application studies. The CLIME as a new module added by Westinghouse for PCS system has been used to simulate the steam condensation process from the inside, the heat transfer of the inner water film, the wall heat conduction, the heat transfer of the outer water film, the water film evaporation, and the radiation heat transfer between different walls.

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

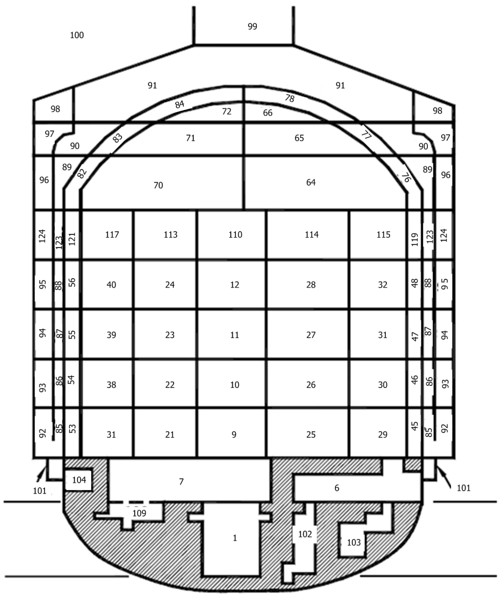

Fig.2 AP1000 WGOTHIC containment model nodes.

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

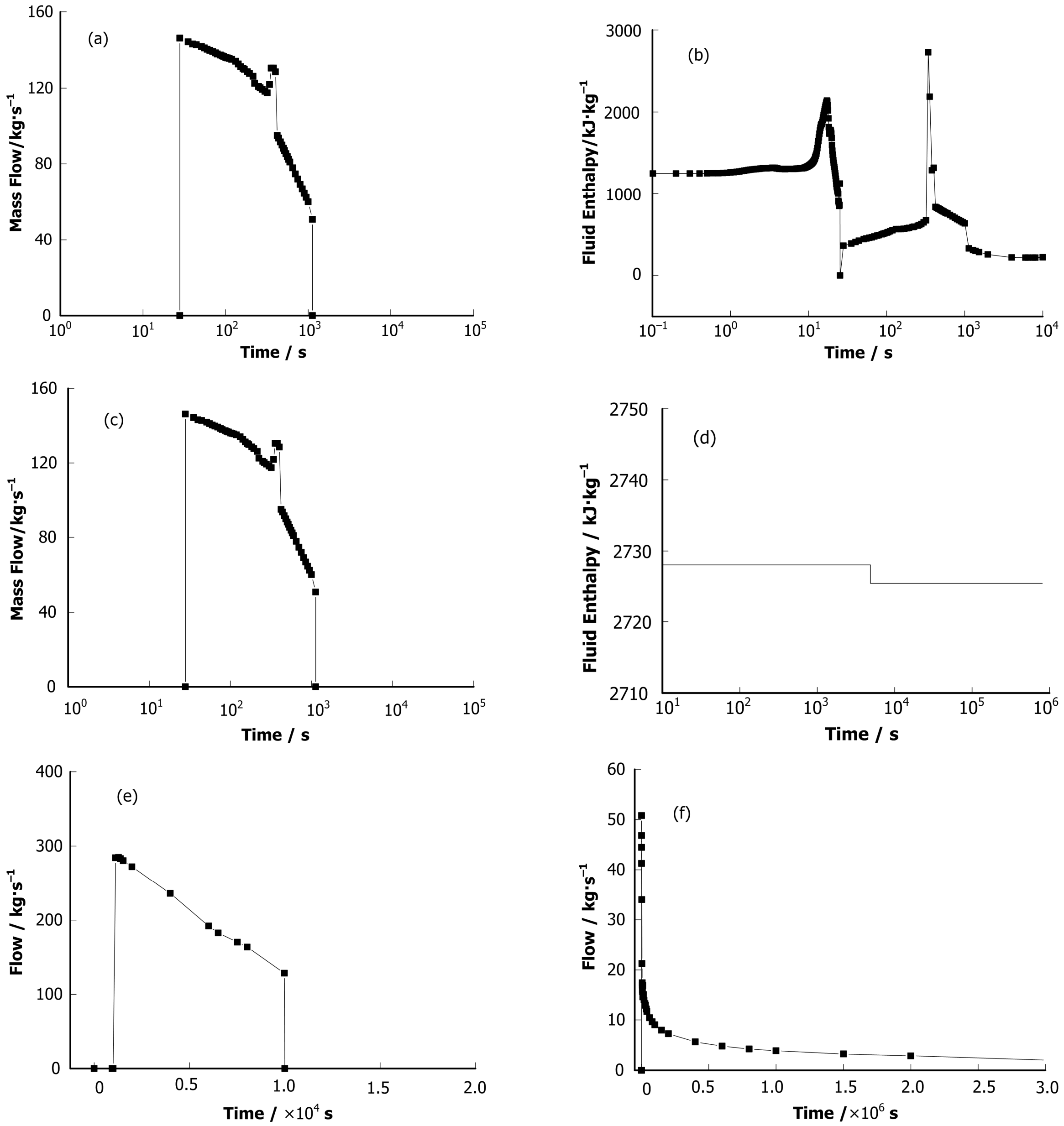

Fig.3 Input functions of WGOTHIC. For DECLG LOCA, (a) Two-phase mass flow, (b) Two-phase fluid enthalpy, (c) Steam mass flow, (d) Steam enthalpy, (e) IRWST injection flow, and (f) Pit injection flow.

2.2 Results and Discussion

As the gauge pressure curve (a) in Fig.4 shows that the pressure in the containment varies form rise to drop after the accident without water in the PCCWST, exceeding the design pressure of the containment (0.407 MPa(g)) at 1 000 s. Subsequently, the pressure further increases and reaches the peak pressure of 2 MPa(g) at 305 217 s (3.5 days), and the shell temperature reaches 213°C. The air-cooling capability of the containment increases with the temperature. At this time, the decay heat is 14 MW, and the core decay heat and the air-cooling capacity reach a balance. Therefore, the containment temperature and pressure gradually decrease with the decay heat. If the containment has sufficient pressure capacity, a fully passive core cooling can be achieved without cooling water in the PCCWST. However, in terms of the practical engineering, it is difficult for a large pressure vessel with the free volume of 5.83×10^4 m^3 to achieve this situation.

The pressure curve in Fig. 4(b) shows that the containment pressure quickly rises, when the AP1000 NPP is not supplied with cooling water after 72 h in a timely manner,. 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 the 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, leading to a potential 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), 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 m^3 cooling water. Although the containment pressure is greater than the design pressure, the AP1000 containment yield limit pressure is approximately 0.6 MPa(g), indicating the high probability that the containment will remain intact.

The pressure curve (d) in Fig.4 shows that the maximum containment pressure reaches 0.403 MPa(g), and the maximum temperature reaches 141ºC, when the cooling-water inventory in the AP1000 NPP PCCWST maintains for 30 days (when no cooling water is supplied). 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 decay heat of the core is less than 6 MW, and the containment maintains a relatively high pressure and temperature. In case that 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 curves of the containment. Because the containment is saturated after the accident, the temperature pressure curves converge.

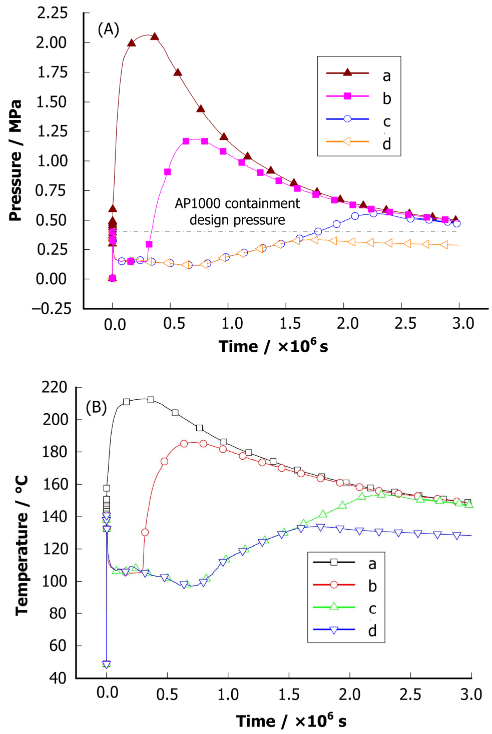

Fig.4 Long-term containment pressure and temperature curves for different cases. (A) Gauge pressure, (B)Temperature. For PCCWST, (a) Without water, (b) 72-h water amount loaded, (c) 19-d water amount loaded, (d) 30-d water amount loaded.

Table 1 lists the limiting case and the 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

	Peak pressure / MPa(g)	Peak temperature / ℃	Cooling water / m^3
No cooling water after accident	2.0	213	None
Cooling water inventory for 72 h	1.183	186	2217.00
Cooling water inventory for 20 h	0.56	153	5673.00
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, there are 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 little effect on the overall heat transfer. Fig.5 shows the pressure curves of the containment for three different wall thicknesses. The temperature curves show a similar trend. The WGOTHIC-calculated values are shown in Table 2.

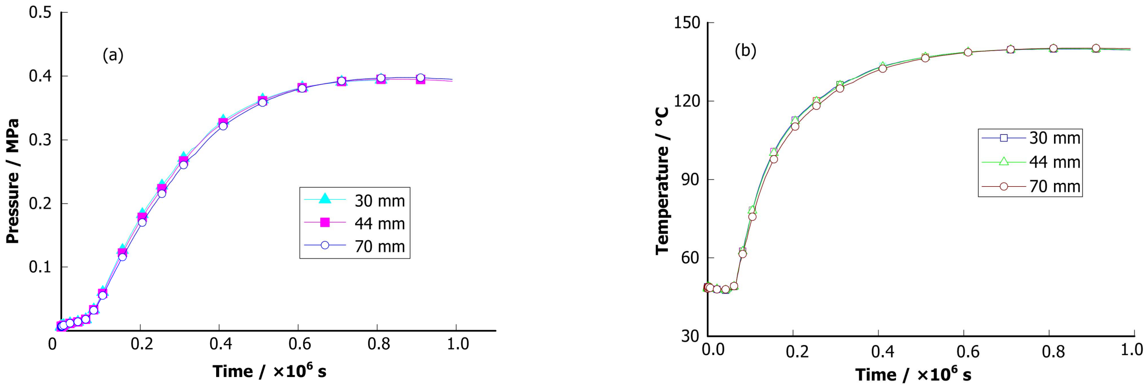

Fig.5 The pressure and temperature curves for the WGOTHIC AP1000 long-term cooling model obtained with different containment-wall thicknesses. (a) Pressure curve, and (b) temperature curve.

Table 2 Comparison of AP1000 pressures and different containment thicknesses

Case	Wall thickness / mm	Maximum pressure / Pa(g)	Design pressure / MPa(g)
1	30	0.395	0.278
2	44.4*	0.396	0.407
3	70	0.399	0.649

* AP1000 design thickness.

The containment design pressure varies significantly, but the peak pressure inside the containment remains relatively stable. This effect is mainly observed because the design pressure increases with the 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[11] for a cylinder with the minimum allowable thickness is adopted for the wall-thickness calculation of the AP1000 containment as follows.

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

Where P is the design pressure, R is the radius of safety containment, 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 the 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 improvements and structure verification

Because of the constant evaporation and condensation of the AP1000 safety-containment internal working-fluid, the heat dissipates from the core to the containment. Containment cooling is equivalent to core cooling in long-term cooling. 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 the cooling water is exhausted, the passive containment cooling water inventory, the PCS air cooling capacity, the shield building design, and the containment design pressure are increased.

In actuality, 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 it does expand the PCCWST tank diameter, increasing the wall thickness of the containment 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 the cooling water of 3000 m^3, to guarantee fulfillment of the 72 h cooling requirement. In the new design, the corresponding PCCWST size is enlarged. In addition, the containment-wall thickness of the shield plant is increased in consideration of the possibility of an 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 the water in the tank, the 35% water mass is distributed uniformly onto the bottom of the tank, as shown in Fig.7(c).

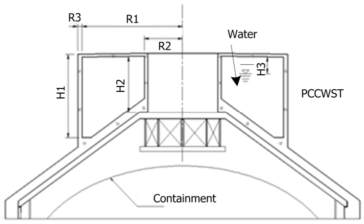

Fig.6 Key dimensions of PCCWST.

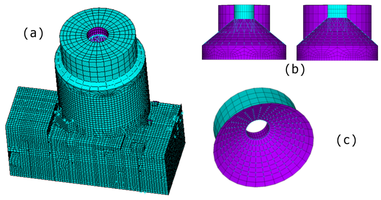

Fig.7 The finite element model of the improved AP1000 shield building.

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

Schemes	Water tank / m^3	Nuclear island mass /t	Shield building thickness / mm	R1 / mm	R2 / mm	R3/ mm	H1 / mm	H2 / mm	H3 / mm
Original	3000	1.28×10^5	915	12963	5334	610	10294	5973	1601
New	6000	1.35×10^5	1200	17800	5400	610	14010	5135	1981

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 with the amount of water and an enlargement of the concrete components. To stabile 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[12] 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 / $\times10^5$kN	NS shear /$\times10^5$ kN	VT reaction /$\times10^5$ kN
Original	5.27	4.31	5.77
New	5.73	4.61	6.72

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 the active earth pressure and the passive earth pressure. The three safety factors of 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			
	Effect of groundwater	Maximum flood effect	EW	NS	Axis 1	Axis 11	Axis I	Axis WSB
Original	3.70	3.51	1.22	1.26	1.48	1.52	1.34	1.25
New	3.91	3.72	1.15	1.22	1.38	1.42	1.25	1.20

The axis positions in Table 5 are shown in Fig.8. All three safety factors meet the original AP1000 civil structure design criteria.

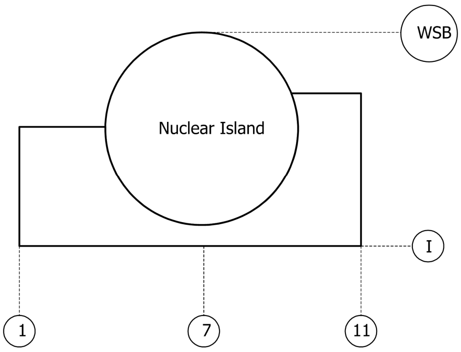

Fig.8 The stability analysis positions.

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 and a relatively large ultimate air heat sink, this AP1000 reactor can achieve completely passive cooling without the 72 h limit, when the core power, containment and shield building are reasonably matched. In this paper, the PCCWST tank diameter and the amount of water loaded to 6000 m^3 increase with the wall thickness of the containment to 65 mm, and the containment design pressure to 0.6 MPa(g)). Because the amount of water in the PCCWST tank is sufficient for 20 days of spray, at which time the decay heat is 7 MW, the containment pressure is less than the design pressure, therefore, the air cooling can dissipate the core decay heat. The new shield building using ANSYS shows that the new design meets seismic requirements.

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