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RESEARCH ON THE PASSIVE SAFETY SYSTEM DESIGN DURING ACP100+

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ABSTRACT: ACP100+ was developed Based on ACP100 which is aimed to enhance the safety further. Inner PRZ and small steel containment design was adopted. The strategy of the emergency core cooling, pressure controlling in the containment and long-term cooling during LOCA are proposed. According to the elementary calculation and analysis, the accumulators can be cancelled for the ACP100+ and the safety injection system gets simpler. The release of mass and energy can be controlled more easily due to the smaller size of break based on pressure restrained pool and containment pool above the small steel containment. Meanwhile the long-term residual heat can the taken out through the pool above the containment based on the natural convection and the inherent safety can be enhanced more.
KEYWORDS: integral small reactor; loss of coolant accident; small steel containment; accumulator

1. Background

SMR is suitable for small electricity grid, district heating, process heating supply and seawater desalination. According to different condition, different counties have different goals in China. In north of China, The demand of energy for city heat consumes is several hundreds of millions tons coal per year, sharing over 10% that the total energy consumption. Due to air pollution in winter, SMR district heating is one of the choices. While in east China, Energy consumption industry in our country, such as building materials, metallurgy, chemical engineering etc, set up their own thermal power plant. The emission occupies over 70% of the total emission in our country. Most of industries locate in east China coastal areas, the serious lack of fresh water resources having become the bottleneck of economic. So SMR used for process heating supply and seawater desalination is also one of the choices. In outlying areas of China, such as mountain area and islands, SMR will be the best choice for electricity generation[1].

Since the 2010, one kind of small and medium size water cooled pressurized reactor called ACP100[2] has developed by China National Nuclear Corporation (CNNC). ACP100 is an innovative reactor based on existing PWR technology; “passive” safety system and “integrated” reactor design technology were adopted. Through about 4 year’s development, Overall design, conceptual design and basic design has finished step by step. A number of testing facilities are constructed. R&D on safety related experiments will be finished in the following 1 years. The construction of the ACP100 will be planned to start at 2016.

According to the feedback of the design of the ACP100, more advanced SMR ACP100+ is developed. The design of ACP100+ aimed to simplify the system design meanwhile the safety can be enhanced farther. This paper focused on reducing the probability and consequence of the loss of coolant accident (LOCA) and optimizing the safety system in the development progress of ACP100+. Meanwhile the validity of the emergence core cooling system (ECCS) and long term cooling system will be demonstrated through calculating analysis.

2. How to reduce the probability and consequence of LOCA according to design

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2.1. Decrease the size and amount of the pipes connect to the primary coolant pipe

Integral reactor vessel design is adopted by the ACP100 and ACP100+ reactor, the integral design of the reactor cooling system (RCS) contains no large primary coolant piping, which significantly reduces the flow area of postulated loss of coolant accidents. The sizes of pipes which are connected to reactor coolant system (RCS) determine the largest break size. The pipes connected to the primary coolant pipe for the ACP100 are shown in Table1. The largest break size is 109.54mm.

During the design of ACP100+, first of all the inner pressurizer is used instead of the outer pressurizer, the surge line can be eliminated, and then the PRHR locate in the secondary loop, PRHR line can be eliminated. Through the restrainer the RHR line can be decreased to 49.22mm which is same as Spray line.

According to the improvement above, the largest break size of ACP100+ can be decreased to 49.22mm from 109.54mm. Otherwise the size of DVI line should be demonstrated if it can be decreased to 49.22mm.

Table 1 Comparison of the largest break size between ACP100 and ACP100+

Potential break location	Potential break size in ACP100 (mm)	Potential break size in ACP100+(mm)
PRZ Surge line	87.32	No
PRHR line	109.54	No
RHR line	109.54	49.22(restrainer)
Spray line	49.22	49.22
DVI line	87.32	49.22(to be demonstrated)

2.2. Immerged steal compact containment is adopted

The immerged steal compact containment is adopted in the design of ACP100+ as the third barrier instead of the large concrete containment in the design of ACP100. the steal shell can be used as heat exchanger the reliability is higher than the traditional containment cooling system. The comparison of containment parameters are shown in table 2.

The largest break size decreased from 109.54mm to 49.22mm which is benefit for the pressure control during LOCA accident and the design pressure is higher during the design of ACP100+, so the free volume in containment of ACP100+ is only 1580 m^3 which is almost 1/10 of the ACP100.

Table 2 Comparison of the containment parameters

	ACP100	ACP100+
Containment type	concrete	Steal
Diameter, m	28	15
Height, m	37.5	18
Thickness, mm	-	45
total volume, m^3	-	2740
free volume, m^3	14700	1580
design pressure, MPa	0.46(abs)	1.15(abs)

Based on the design improvement of ACP100+, the safety systems need to be modified for more effective and simplified mitigation of LOCA.

3. Mitigation strategy of LOCA during ACP100+

Once the LOCA happen, three main safety function need to perform immediately which are cool the core, control containment pressure and long-term remove the decay heat. This chapter will put forward Mitigation strategy of LOCA based on the ACP100+ and demonstrate availability of mitigation strategy.

The passive safety system of ACP100+ is illustrated in figure 1, which provides mitigation of all design basis accidents without the need for AC electrical power for a period of at least seven days.

The passive safety system of ACP100+ contain two core makeup tanks (CMTs), two in-containment water pool(IWPs)where the medium pressure safety system is eliminated due to largest break size was reduced to only 49.22mm. in-containment water pool(IWPs)also undertake repression function which are used to depress the pressure in containment. Otherwise an automatic depressurization system (ADS), two passive residual heat removal (PRHR) heat exchangers locate in the outer-containment water pool (OWP) which is the ultimate heat sink. The water amount in the outer-containment water pool (OWP) can ensure decay heat removal availably at least seven days.

3.1. Cool the core

3.1.1. Design of emergency core cooling system

After LOCA happen, emergency core cooling through coolant makeup from safety injection system is most important mitigation measures. Three pressure level safety injection system are usually used to ensure core cooling and avoid the temperature of fuel exceed limitation. during ACP100[2], Three pressure level safety injection system rely on the core makeup tanks (CMTs), accumulators (ACCs) and inner refuel water storage tank(IRWST)respectively which are all passive.

The high pressure safety system is designed to feed water for the small break LOCA, for this purpose ACP100+ and ACP100 are similar. The core makeup tank (CMT) is adopted all the same in ACP100+.

The medium pressure safety system usually aims at relative large break LOCA when water in the lower plenum loss, Accumulators (ACCs) is the usually adopted to feed water to the lower plenum rapidly so that the core reflooding phase will come earlier. For the ACP100+ the largest break size is 49.22mm that is less than ACP100, there are enough water in the lower plenum all the time during the accident. The function of ACCs is weak. So Accumulators (ACCs) are eliminated in ACP100+.

The low pressure safety system aims at mitigate the LOCA accident when the reactor pressure is low, the long term cooling is crucial during this phase. For this purpose ACP100+ and ACP100 are similar. So the in-containment water pool(IWPs) is adopted all the same in ACP100+. When the water level in the in-containment water pool is lower than the location of the suck nozzle in the low pressure safety system the recirculation systems start up.

3.1.2. The function of ACCs

In this paper analysis was performed using best estimate LOCA safety evaluation code RELAP5/MOD3.2 [3] which is capable to address LOCA safety analysis from the smallest break size to the largest break size in ACP100 and ACP100+.

For the ACP100+ the diameter of DVI line is reduced to 49.22mm that is need to demonstrate it is enough to feed water to the core. The doubled ended guillotine types break of DVI was simulate where ACCs start up or not. the results of calculate are shown in figure2-figure4.

Figure 2 and Figure 3 indicates even the diameter of DVI line is reduced to 49.22mm which is enough to cooling the core, the safety injection flow rate are shown in figure 4 and figure 5.

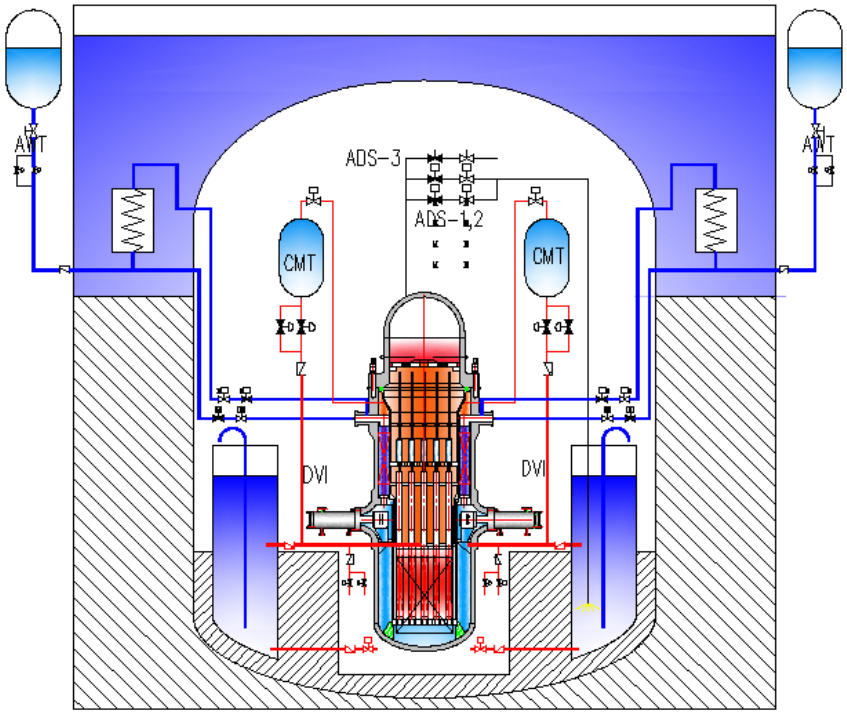


Figure 1. Sketch of ACP100+ passive safety system

Figure 2 compares that the core water level with and without ACCs, there are no obvious difference between these two cases. Figure 4 and figure 5 indicate that the water in ACCs flow into reactor coolant system only in the early phase of the accident. The function of ACCs is not important for the core cooling when the break size is reduced to 49.22mm because the core water level always maintain almost above 1.1m which is the half level of the core.

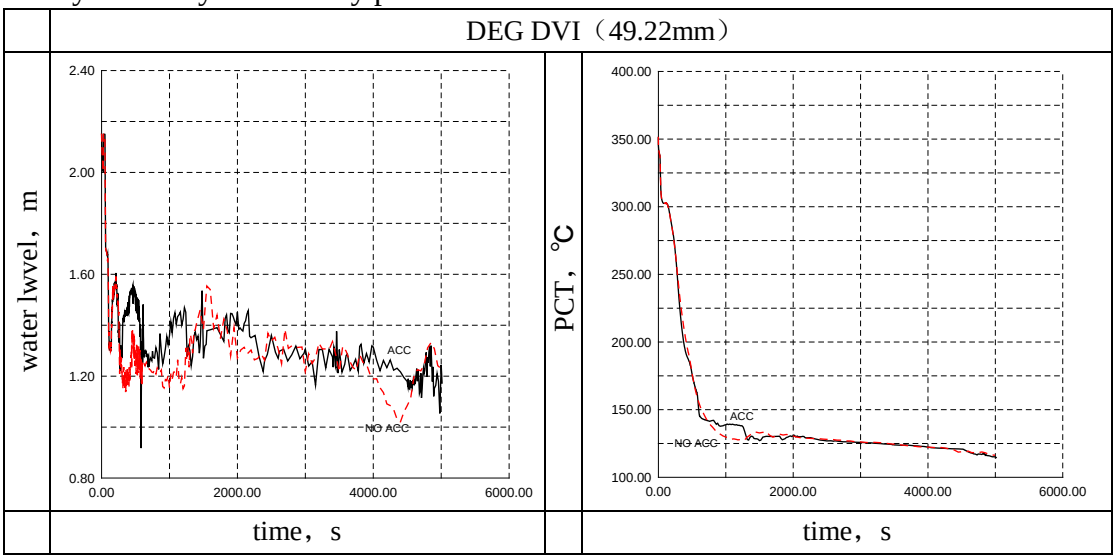


Figure 2 Core water level

Figure 3 Peak cladding temperature

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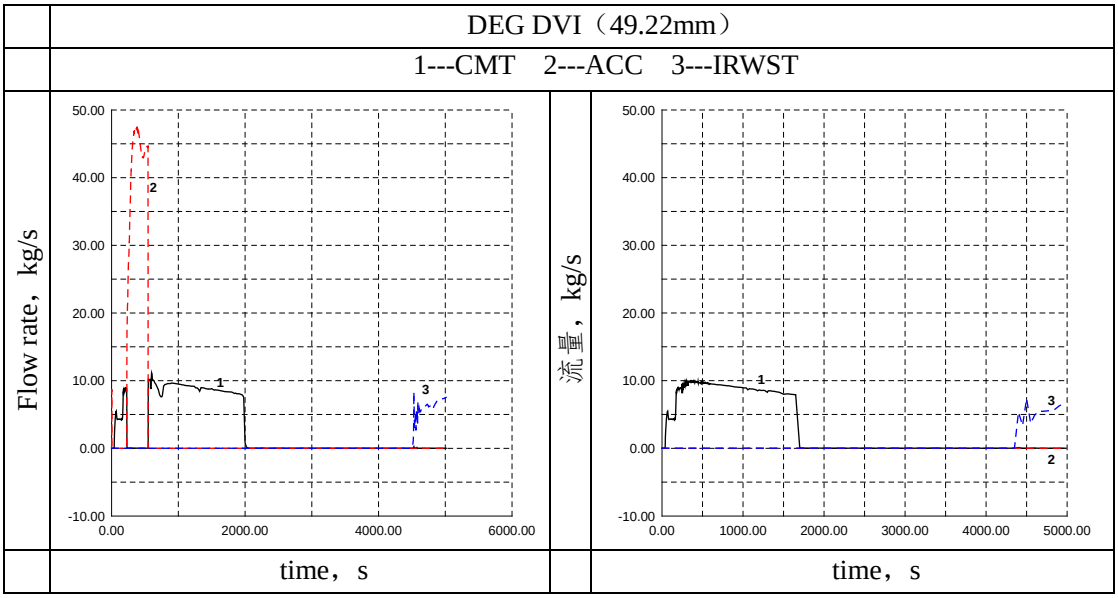


Figure 4 safety injection flow rate（with ACC）

Figure 5 safety injection flow rate（no ACC）

For making the function of ACCs known the sensitivity analysis of break spectrum are performed. The break sizes cover 9.5mm-200mm, eight cases are analysis shown in table3.

When the break size is less than 49.22mm, the loss rate of coolant is slow. The temperature of cladding has not risen during the progress of accident. ACCs have no influence for the mitigation of accident.

When the break size achieves 80mm, once ACCs start up, the peak cladding temperature (PCT) is even more than the case without ACCs. Figure 6 illustrate that the core water level is lower for the case of ACCs launched into than that of without ACCs in the period between blowdown and reflood stage, so that the peak cladding temperature (PCT) is lower for the case of ACCs launched into which is shown in figure 7. That is because the ACCs launched in suddenly and the flowrate is obviously higher than the CMT, the water temperature in ACCs is lower than that in the downcomer of the reactor vessel where the steam will condense suddenly, that will result in the pressure drop in the downcomer of the reactor vessel, the water in the core will flow backwards out of the core. But the period is very short, so the PCT is over only 19℃ for the case of ACCs launched into that the case of without ACCs.

With the break size increase more, the benefit of ACCs will come out gradually. If the diameter of DVI increases to 200mm the PCT is obviously less for the case of ACCs launched into than the case of without ACCs.

The calculations above indicate that ACCs is crucial for the larger break size. It is reasonable that eliminating the ACCs in the ACP100+.

Table 3 PCT of different break size and diameter of DVI

Break size/mm	With or Without ACCs	PCT/ ℃
9.5mm DVI break	With	350
	Without	350
30 mm DVI break	With	350
	Without	350
49.22mm DEG DVI	With	350
	Without	350
80mm DEG DVI	With	388
	Without	369
100mm DEG DVI	With	418

	Without	419
120mm DEG DVI	With	473
	Without	499
150mm DEG DVI	With	828
	Without	967
200mm DEG DVI	With	1165
	Without	1401

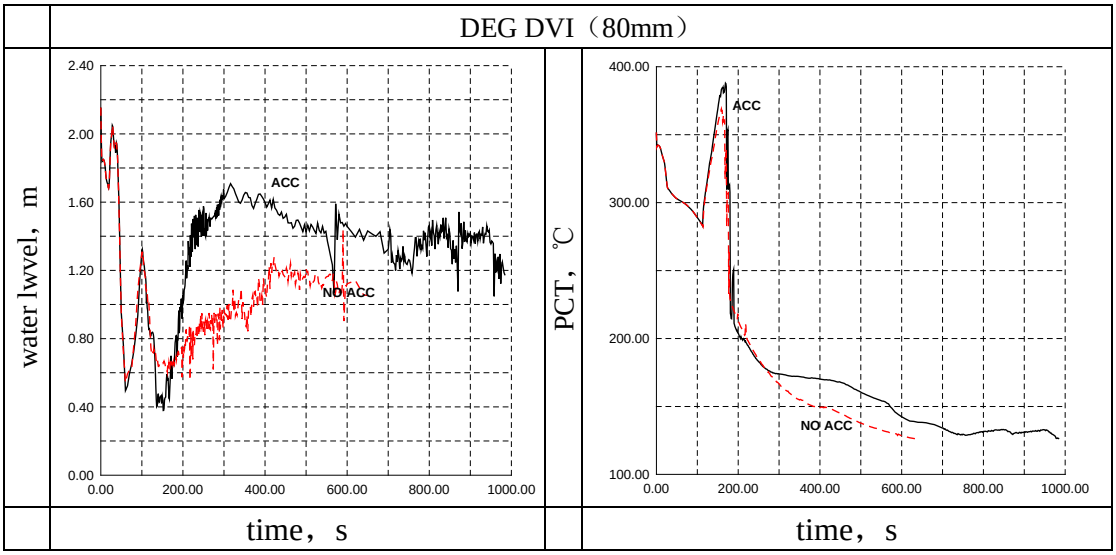


Figure 6 Core water level

Figure 7 Peak cladding temperature

3.2. Control the pressure in the containment

The pressure in the containment increases sharply due to the mass and energy release after the LOCA accident. For the steal compact containment the advantage are higher design pressure(1.15MPa) and less break size(49.22mm), the disadvantage is small free volume. This chapter will demonstrate the availability of the containment pressure control measures. The Initial and boundary conditions of the containment are shown in table 3.

Figure 8 indicate even the break size reduce from 100mm to 49.22mm the containment pressure will still over the design pressure limit. The repression function derived from IWPs can restrict the pressure below the design pressure limit. The results are shown on figure 9.

Table 3 Initial and boundary conditions of the containment

Outer wall heat transfer coefficient	$Nu = 0.15(\mathrm{Pr} \bullet Gr)^{0.25}$ [3]
Area of upper hemisphere, m^2	195
Total immerged area, m^2	289
Wall thickness, mm	45
Thermal conduction coefficient,W/(m· ℃)	20 ℃54.6[3], 200 ℃48.8
Water temperature in OWP, ℃	50
Water temperature in OWP, ℃	55
Free volume in containment, m^3	1580
Design pressure, MPa	1.15

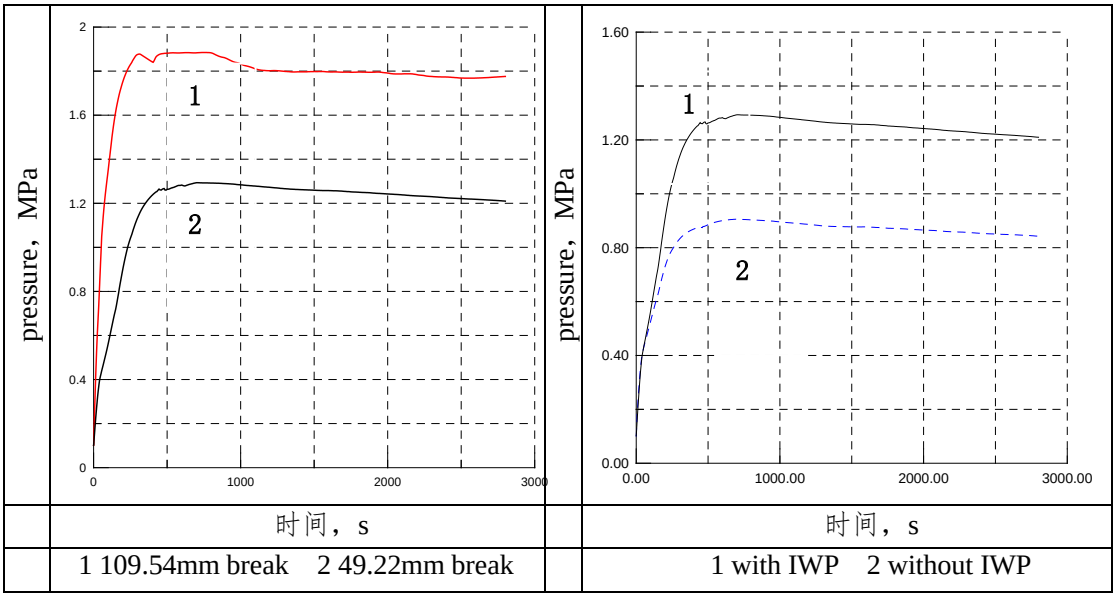


Figure 8 containment pressure

Figure 9 containment pressure (49.22mm break)

3.3. Long term cooling

When the stage 3 valves open in the automatic depressurization system (ADS), the isolation valve connecting the IWPs and DVI line will open. The low pressure safety injection phase begins.

In the early period of the low pressure safety injection phase which is called direct injection period, the cooling water comes from IWPs. Figure 10 indicate the flowrate is enough to cooling the core, the core collapse water level is always above 1.1m.

In the later period of the low pressure safety injection phase which is called recirculation injection period, the cooling water comes from lower containment cavity. The water in the lower containment cavity comes from the steam condensate rely on the steal wall of containment. In this period the OWP had undertaken the function of ultimate heat sink. Figure 11 indicates the natural circulation can be founded long-term.

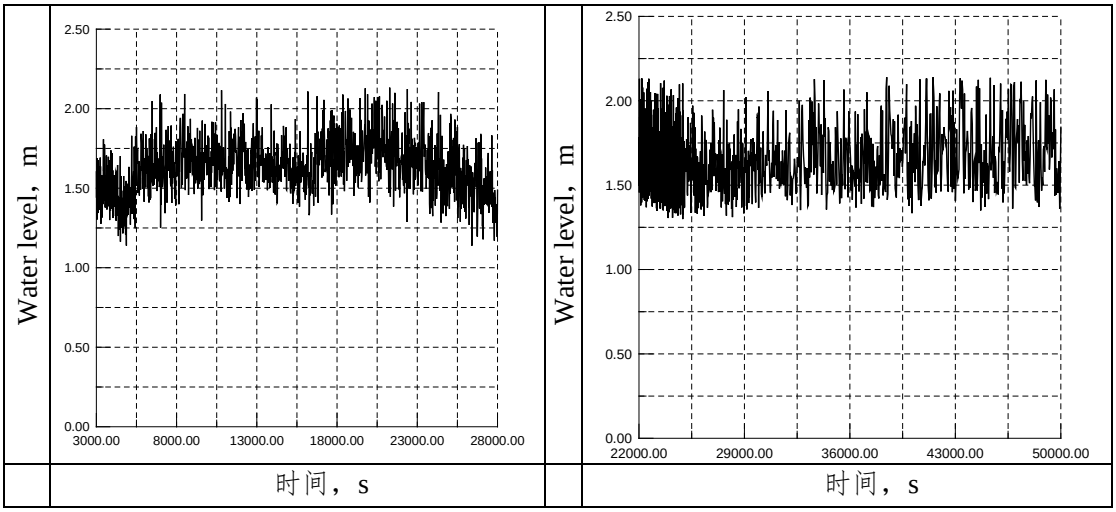


Figure 10 core collapse water level during direct injection period

Figure 11 core collapse water level during recirculation injection period

4. Conclusions

In this paper the mitigation strategy of ACP100+ SMR was proposed, and through calculation analysis, main conclusions are below:

1. The break size can be reduced more through modified design in ACP100+ SMR, that will

bring more safety and simplified system, such as less pipes connected to RCS and eliminating the ACCs.

2. The design of steal compact containment is available for the SMR ACP100+, but the repression pool is needed due to small free volume in the compact containment.
3. The heat transfer capability of natural convection is enough to remove decay heat of the ACP100+ due to the small thermal power; the containment wall is more reliable heat exchanger than the traditional residual removal systems which need signal to open the valve.

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