Overview of methods for vessel integrity maintenance under severe accident in PWR

N B Lei¹²
¹China Nuclear Power Engineering Co., Ltd, Haidian District, Beijing, China
E-mail: leinb@cnpe.cc

Abstract. The PWR (pressurized water reactor) vessel contains the whole core and almost all the radioactive products. After severe accident, core will be molten due to loss of cooling and relocate to the lower head of vessel finally. In this situation if the integrity of vessel could be maintained by various methods, mass fraction of radioactive products will be retained in the vessel and the accident consequence will be mitigated. After Fukushima accident, Chinese government raises the “practically elimination” request to the NPP in plan, and it is a meaningful approach to meet this request by maintaining the integrity of vessel after severe accident. In this paper, the methods of maintaining integrity of vessel implemented in mainstream advanced PWR are classified and introduced by the decay heat removal approach.

1. Introduction
Nuclear power is green, clean and high-efficiency energy, but now it faces challenges in many countries, which is induced by the potential radioactivity release under severe accident. In order to strengthen the public confidence to nuclear power, various countermeasures were developed to prevent and mitigate this problem. In NPP (nuclear power plant), the reactor vessel contains the whole core and almost all the radioactive products, if the integrity of the vessel could be maintained after severe accident, then there will be less or none radioactivity release, like what happened in TMI accident; the counterexample is the Fukushima accident.

In 2012, Chinese government raises the “practically elimination” request to the NPPs in plan. If appropriate measures are launched after severe accident to make the integrity of vessel could be maintained, then the ex-vessel phenomena that may cause containment damage such as DCH (direct containment heating), MCCI (molten core-concrete interaction) and FCI (fuel-coolant interaction) will be averted, this is meaningful to meet the “practically elimination” request.

2. Methods for vessel integrity maintenance
The essential factor threatened the vessel integrity is the decay heat of core. Consequently, according to the different decay heat removal measures, the methods for vessel integrity maintenance implemented in mainstream advanced PWR (pressurized water reactor) are classified.

2.1. Primary circuit depressurization combined with water makeup
Since the cause of severe accident is insufficiency of core inventory, the obvious countermeasure is to inject water to primary circuit, which could remove decay heat to prevent core degradation. The precondition of water makeup is primary circuit depressurization because the available water sources are low-pressure. Depressurization could also avoid the hot leg or SG hot tubes creep-rupture, while
the latter could lead to direct release to environment.

2.1.1. HPR1000. In HPR1000 [1] design, two sets of fast depressurization valves are launched to carry out the depressurization function under severe accident, as shown in Figure 1. Each set has a drain capacity of 525t/h on the design pressure, driven by AC power while in SBO condition by accumulator, and release to quench tank. When the core exit temperature exceeds 650℃ in severe accident, operator will open these valves to depressurize primary circuit rapidly.

![Figure 1. Fast depressurization valves in HPR1000.](image_url)

2.1.2. EPR. Similar to HPR1000 design, EPR [2] also launches two sets of fast depressurization valves, as shown in Figure 2. Just one set is capable to depressurize primary circuit to several bar in virtue of the drain capacity of 900t/h on the design pressure. It is driven by SBO diesel generator or specific long-term accumulator, and release to quench tank. The activation condition is the same to HPR1000.

![Figure 2. Fast depressurization valves in EPR.](image_url)

2.1.3. AP1000. Different from the manual-operated depressurization system in HPR1000 and EPR, AP1000 [3] implemented automatic depressurization system consisting of 4 levels automatic depressurization valves, each level is composed by two sets, as shown in Figure 3. L1~L3 valves are located at the top of the pressurizer and drain to IRWST (inner refuelling water storage tank); L4 valves are connected to hot leg and drain to containment. As the name implies, when the condition is met, it will run automatically.

![Figure 3. Automatic depressurization system in AP1000.](image_url)

![Figure 4. Passive residual heat removal system of AP1000.](image_url)
2.1.4. Water makeup. If the depressurization acted successfully, then the water injection to primary circuit can be applied. Available water source may be accumulator, recovered low-pressure safety injection or the new launched movable pump and fire engine after Fukushima accident. It should be noted that water injection has both positive and negative effects. The former one includes: decay heat could be removed then core degradation will be prevented; radioactive products could be retained in water and the release fraction is reduced. The latter one includes: if the injection rate is not large enough then there will be steam-cladding oxidation that generates hydrogen; vessel will suffer thermal shock; the hot core will be quenched to form debris bed. In a word, the injection occasion should be selected carefully according to severe accident progression and available water inventory.

2.2. Passive heat removal from primary circuit
As an advanced passive reactor, AP1000 launches the PRHR (passive residual heat removal system), as shown in Figure 4. The main component of PRHR is the C-type heat exchanger submerged in IRWST. It locates above the reactor, inlet is connected to the hot leg of first loop while outlet is connected to the cold plenum of the second SG (steam generator) lower head. It is fulfilled with core coolant while normal operation, the pressure is the same with primary circuit, and the temperature is the same with the cold water in IRWST. Under accident condition, the driven force induced by gravity and temperature difference will form the natural circulation between primary circuit and the C-type heat exchanger to remove decay heat to IRWST. After the water in IRWST is boiled, the steam will condense on the inner surface of containment then flow back to IRWST.

2.3. Passive heat removal from secondary circuit
In traditional PWR, the auxiliary feedwater system could supply feedwater to SG by pump under accident condition to cool the core by heat conduction from primary circuit to secondary circuit. This measure will be invalid if pump or water source is unavailable. Accounting for this, PRS (passive secondary-side heat removal system) is implemented in some advanced Gen-III reactors.

2.3.1. HPR1000. In HPR1000 design, PRS consists of three sets while each set corresponds to one SG. As shown in Figure 5, the inlet of PRS is connected with the steam outlet of SG, while the outlet of PRS is connected with the feedwater inlet of SG. In normal operation, PRS is isolated; if SBO (station black out) plus TDP (turbine-driven feedwater pump) failure or LOFW (loss of total feedwater) happened, PRS will be activated automatically. The steam generated in SG flows into heat exchanger submerged in the heat exchange tank and is condensed, then the water flows back to SG. Through this natural circulation, the decay heat is removed from core to SG then to the heat exchange tank. If the SG secondary side water level decreased to a certain value, the water in makeup tank could inject to SG to maintain the water level.

![Figure 5. Passive secondary-side heat removal system in HPR1000 (one set).](image)

![Figure 6. Passive auxiliary feedwater system in APR1400/APR+ (one set).](image)
2.3.2. APR1400/APR+. PAFS (passive auxiliary feedwater system) is one of the advanced safety characteristics of APR+ [4], which is designed to replace the conventional active auxiliary feedwater system. It consists of two sets, and each set with the heat removal capacity of 129.8 MW is capable of remove the total decay heat. As Figure 6 shows, when PAFS is activated, the steam generated in SG flows through main steam line and steam supply line into condensation heat exchanger submerged in PCCT (passive condensate cooling tank), then is condensed into water and flows back to SG through return water line and feedwater line. Through this natural circulation, decay heat is removed to PCCT finally.

2.4. Primary circuit depressurization combined with cavity injection
If the core cooling has lost for a long time, core will be molten and relocate to the lower head of vessel, finally form molten pool. In this situation, the heat removal measures mentioned before couldn’t work because the core has lost the geometry for cooling. One feasible solution is to submerge the lower head by injecting water to cavity, so the molten pool decay heat could be removed from outer surface of lower head to maintain the integrity of vessel. This methodology is called IVR (in-vessel retention), and was raised by Theofanous and applied in Lovisa VVER-440 [5] in Finland. Now it was widely implemented in Gen-III PWR.

The precondition of the success of IVR is primary circuit depressurization mentioned before to reduce the stress of lower head.

2.4.1. AP1000. Westinghouse implemented the IVR methodology in AP1000 design, as shown in Figure 7. Under severe accident condition, operator could open the valves in recirculation line connected IRWST and recirculation sump, then the water will inject to the cavity from IRWST. The water level in cavity is high enough to ensure the flow between vessel and insulation layer is two-phase, which could increase the CHF (critical heat flux) of outer surface of vessel. The steam generated will condense by containment and flow back to IRWST.

2.4.2. HPR1000. Different from AP1000, CIS (cavity injection system) in HPR1000 consists of active set and passive set, as shown in Figure 8. Under severe accident, when core exiting temperature exceeds 650°C, CIS will be activated to inject water to the gap between vessel and insulation layer to submerge the lower head. The active set runs under all conditions except SBO, it pumps water from IRWST; the passive set is designed to run if SBO happened, in this situation the water in passive cavity injection tank will be driven by gravity.

3. Assessment of methods for vessel integrity maintenance

3.1. Assessment of primary circuit depressurization combined with water makeup
As mentioned in last section, the precondition of primary circuit makeup is depressurization. Whether this measure valid or not is up to the accident progress and makeup rate. The assessment here is based on loss of AC power in HPR1000 with following assumptions: 1) loss of AC power at 0s; 2) turbine-
driven auxiliary feedwater pump is invalid; 3) PRS is invalid; 4) when core exiting temperature exceeds 650°C one set of depressurization valve is manually opened; 5) the low pressure safety injection is recovered when primary circuit pressure decreases to 1.7MPa. Table 1 lists the accident progress. Figure 9 shows the primary circuit pressure varying with time. From these we can conclude that: 1) the depressurization action get success, primary circuit pressure decreases to a low value; 2) water makeup in this condition maintains the integrity of vessel.

| Event                                      | Time (s) |
|--------------------------------------------|----------|
| Loss of AC power                           | 0        |
| core exiting temperature exceeds 650°C, depressurization valve open | 7991     |
| Accumulator injection starts               | 8641     |
| Low pressure safety injection recovers     | 13116    |
| Vessel failure                             | N/A      |

Table 1. Accident progress of loss of AC power in HPR1000.

Figure 9. Primary circuit pressure varies with time of HPR1000 (loss of AC power).

3.2. Assessment of passive heat removal from secondary circuit
Here loss of feedwater in HPR1000 is analysed with following assumptions: 1) loss of total feedwater at 0s; 2) PRS is activated automatically; 3) accumulator is valid. Figure 10 and Figure 11 show the primary circuit pressure and temperature varying with time. It can be seen that primary circuit
temperature maintains at a low value, so the core melt couldn’t happen and vessel integrity is maintained.

3.3. Assessment of primary circuit depressurization combined with cavity injection

ROAAM (risk-oriented accident analysis methodology) is widely used in assessing IVR internationally. The precondition of success of IVR is depressurization, and it has been shown that the mainstream Gen-III reactor could meet this in former section. Here we select HPR1000 to do the analysis. Accounting for large LOCA (lost of coolant), medium LOCA, small LOCA and SBO, the key parameters distribution including Zirconium oxidation fraction, mass of stainless-steel and decay heat are given. Based on this, 10000 cases are sampled to calculate the actual heat flux of outer surface of lower head. The comparison between this value and CHF is shown in Figure 12. Almost in all cases the actual heat flux is lower than CHF, just 3 cases give the opposite result, so it is credible to conclude that depressurization combined with cavity injection does work.

![Figure 12. CHF vs actual heat flux of lower head outer surface of HPR1000.](image)

4. Conclusions

Maintaining integrity of vessel under severe accident is a meaningful approach to prevent and mitigate the radioactivity release, which would improve nuclear power safety and strengthen public confidence. In this paper, the measures to maintain integrity of vessel implemented in mainstream advanced Gen-III PWR are classified by the heat removal approach and introduced. The assessment results show that these measures could act the role we want.

References

[1] Xing J 2016 HPR1000: An Advanced PWR Nuclear Power Plant with Active & Passive Safety (Beijing: China Atomic Energy Press)
[2] Zheng H 2010 Comparison of severe accident mitigation measures between EPR and CPR1000 Chi J Nu Sci Engi 30 250-7
[3] Sun H H 2010 AP1000: 3rd Generation Nuclear Power Technology (Beijing: China Electric Power Press)
[4] Kim S, Bae B-U, Cho Y-J, Park Y-S, Kang K-H and Yun B-J 2013 An experimental study on the validation of cooling capability for the Passive Auxiliary Feedwater System (PAFS) condensation heat exchanger Nu Engi Desi 260 54-63
[5] Kymaelaeinen O, Tuomisto H and Theofanous T G 1997 In-vessel retention of corium at the
Lovvisa plant *Nu Engi Desi* **169** 109-30