



depending on the type of accidents. The CP is utilized as a multi-purpose coolant inventory of the large capacity of emergency coolant and spent fuel pool. To sustain the water level for the spent fuel, the inlet of the CFS lines is set 2 m from the bottom of the CCP as shown in Fig. 2 (a). The separate dry cavities and Aux. pools are installed along the side of the CP. The condenser using heat pipes is positioned on the ceiling of the plant building. Figure 2 (b) shows 2 Aux. pools placed on both side of a cavity and connected to the SGs of the RM.

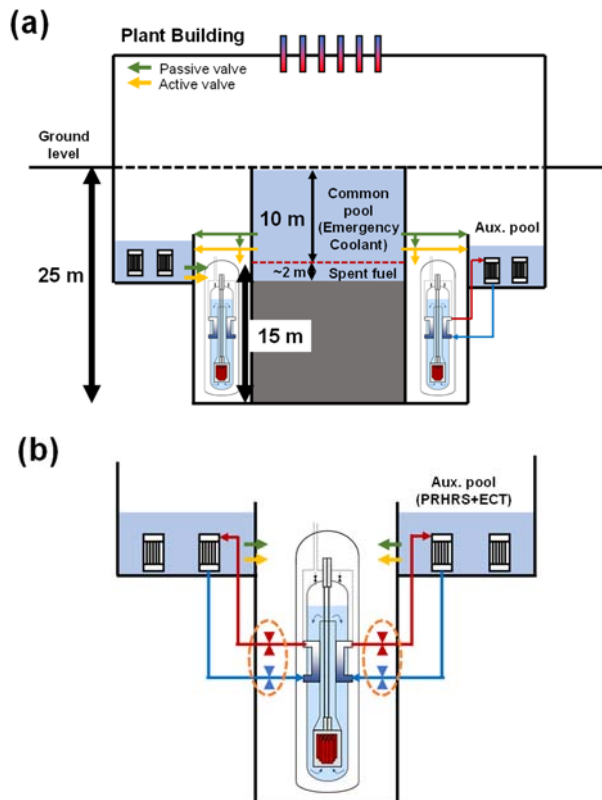


Fig. 2. Conceptual schematic of the CFS  
 (a) whole configuration, (b) PRHRS.

### 2.2. Decay heat removal mechanism under postulated accidents

During the LOCA, the coolant of primary system is leaked into the gap between the RPV and CNV. Otherwise, the steam is released through valves on the

top of the RPV during SBO and other accidents without an action to mitigate overpressure. The cavity is flooded by the CFS actively in case of the LOCA and passively for the SBO, respectively. Accordingly, the decay heat is removed as depicted in Fig. 3. Although the transferred heat induces boiling of the water in the cavity, the water level is maintained in the long-term by condensing the steam released into the plant building and re-collecting the condensate to the cavity. Through the decay heat removal mechanism, the grace period is expected to be prolonged significantly.

### 3. Methodology of coolability assessment

In order to assess the long-term coolability during the LOCA and SBO, the mass depletion of the available emergency coolant was investigated through numerical analysis. The heat transfer and the net steam generation with and without condensate re-collection were evaluated. Conservative engineering assumptions were adopted to assure the feasibility of the proposed safety feature. The mass change of water and steam and heat transfer by boiling and condensation was computed for every second. The calculation was carried out until that the available coolant was depleted or condensation heat transfer was consistently larger than decay heat generation was confirmed. Simultaneous accident occurrence in all 6 RMs was assumed for conservative approach.

#### 3.1. Long-term coolability without condensate re-collection

Compared to the natural convection, the boiling on the outer wall of the CNV is a dominant mechanism to remove the decay heat. Accordingly, heat removal only by boiling heat transfer was assumed in the assessment without condensate re-collection. The decay heat was computed by the approximation formula in Ref. [6]. The operation time was set to 2 years. Assuming that the plant building is open to the atmosphere, the supplied water was saturated at 1 atm. Thus, the mass change of available water over time can be described with the decay heat and the latent heat of vaporization as shown in Eq. (1). The mass of water over time was updated until its total depletion following the algorithm in Fig. 4.

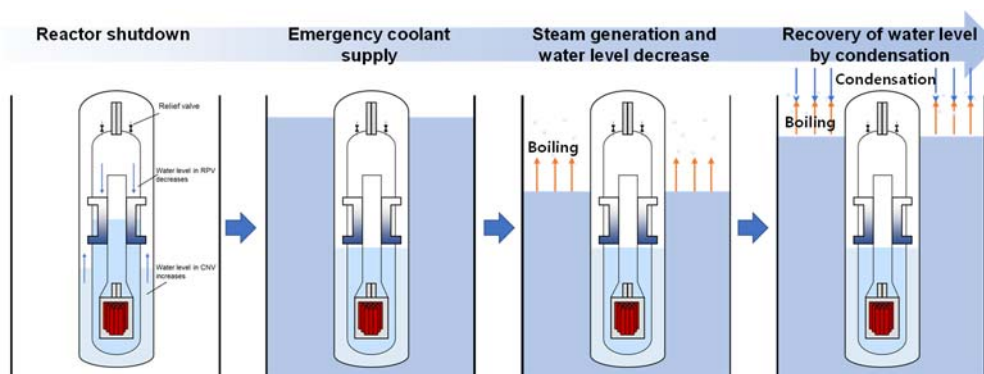


Fig. 3. Accident response processes during LOCA and SBO.

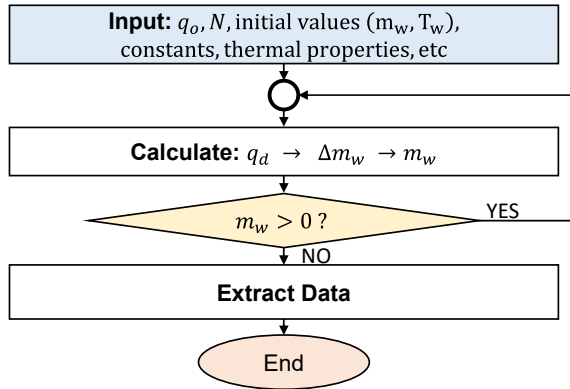


Fig. 4. Flow chart for the assessment of grace period without condensate re-collection.

$$\Delta m_b = -\frac{Q_d}{h_{fg,b}} \quad (1)$$

Here,  $Q_d$ ,  $\Delta m_b$ , and  $h_{fg,b}$  are the decay heat generated for the time interval, mass change of water due to boiling, and latent heat of vaporization, respectively.  $h_{fg,b}$  was calculated as a constant of 2256.5 kJ/kg.

### 3.2. Long-term coolability with condensate re-collection

The mass of available emergency coolant needs to be maintained to enhance long-term coolability. In this study, the stored steam is condensed on the condenser located on the ceiling and collected into the CP and cavities in the plant building. For the assessment with condensate re-collection, the additional heat transfer process by condensation was adopted. Figure 5 shows the simplified flow chart of the algorithm to assess the long-term coolability with condensate re-collection.

The steam generation was calculated by using Eq. (1) with varying latent heat according to pressure condition inside the plant building. However, the temperature of supplied water was set to 40 °C at 1 atm because the spent fuel pool temperature is generally 30-40 °C under normal operation. Thus, the decay heat induces the increase in temperature of the emergency coolant until it reaches saturation assuming subcooled boiling does not occur. The temperature over time was determined by Eq. (2), where  $T_w$ ,  $m_w$  and  $C_{p,w}$  are temperature, mass, and specific heat of water in the cavities, respectively.

$$T_w(t + \Delta t) = T_w(t) + \frac{Q_d(t)}{m_w(t) \cdot C_{p,w}} \quad (2)$$

The steam is condensed in the presence of air in the plant building. To evaluate the condensation heat transfer, a generalized correlation for condensation in the presence of air was adopted [7]. The generated condensate for the time interval was described as Eq. (3). Accordingly, the mass change by net steam-condensate generation was derived as shown in Eq. (4).

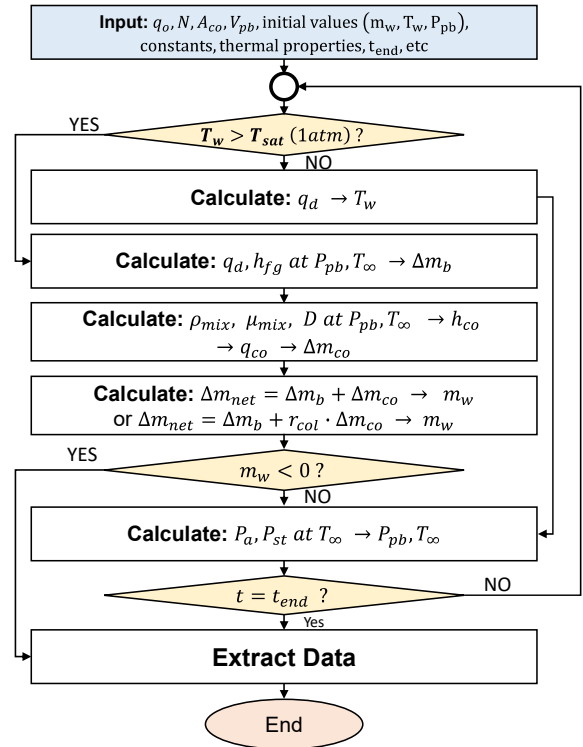


Fig. 5. Flow chart for the assessment of grace period with condensate re-collection.

$$\Delta m_{co} = \frac{Q_{co}}{h_{fg,co}} \quad (3)$$

$$\Delta m_{net} = \Delta m_b + \Delta m_{co} \quad (4)$$

Here,  $Q_{co}$ ,  $h_{fg,co}$ ,  $\Delta m_{net}$ , and  $\Delta m_{co}$  are transferred heat by condensation, latent heat for condensation, net mass change of water, and generated condensate, respectively.

After the temperature exceeds the saturation temperature, heat transfer only by phase change was considered. In other words, the additional sensible heat of water due to pressure change was neglected. The pressure increases as the steam fraction increases in the plant building. To compute the pressure and temperature in the plant building, the mixture of steam and air was assumed as ideal gas. Consequently, adopting ideal gas law and law of partial pressure, Eq. (5) shows how the pressure was determined. The saturation temperature at the updated pressure was set as the initial value of the temperature for next time step. The calculation of the pressure and temperature was iterated until the relative error was less than 1%.

$$P_{pb} = P_a + P_{st} = \frac{n_a RT_\infty}{V_{pb}} + \frac{n_{st} RT_\infty}{V_{pb}} \quad (5)$$

Here,  $P_{pb}$ ,  $P_a$ ,  $P_{st}$ ,  $n_a$ ,  $n_{st}$ , and  $V_{pb}$  are pressure in the plant building, partial pressure of air and steam, mole number of air and steam, and the free volume of the plant building. In this study, the free volume and surface

area of condenser were set to 11,830 m<sup>3</sup> and 260 m<sup>2</sup>, respectively. The temperature of the condenser surface was set to 100 °C.

### 3.3. Long-term coolability with partial condensate re-collection

In the previous section, the full collection of the condensate into the CCP and Aux. pools and cavities was assumed. However, only some part of the generated condensate is expected to be collected because the condensate can be stagnated by the structure in the plant building. Thus, Eq. (4) was modified by adopting the collection ratio  $r_{col}$  as shown in Eq. (6). The time to total depletion of emergency coolant was investigated with the collection ratio from 0 to 0.9 with interval of 0.1.

$$\Delta m_{net} = \Delta m_b + r_{col} \cdot \Delta m_{co} \quad (6)$$

## 4. Results and Discussions

To confirm the effect of the condensate re-collection, the accident mitigation using heat removal only by the latent heat was assessed. The mass of the emergency coolant flooding the cavity during an accident is shown in Fig. 6. Due to the decreasing decay heat over time, the decrease in mass in the cavities was slowed down with time. The grace period, time to total depletion of water in the cavities, achievable for 1 and 6 modules in accidents were 1485 days and 43 days, respectively. The estimated grace periods largely exceed the generally required coping time, 3 days. However, an additional strategy to sustain the mass of available water needs to be sought for indefinite safety even in the case of the accident occurrence in all 6 RMs.

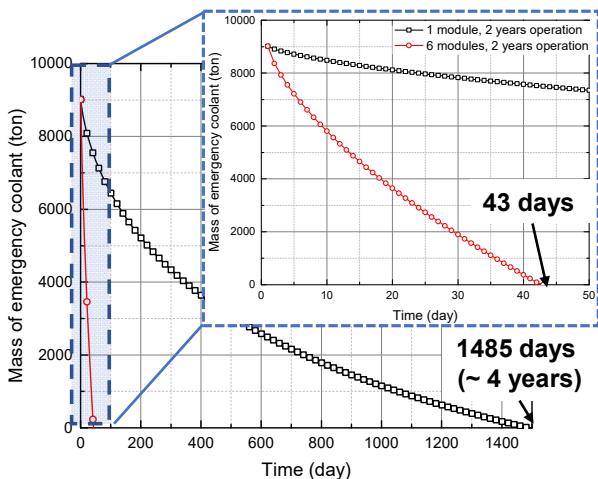


Fig. 6. Mass of the emergency coolant over time without condensate re-collection

The effects of condensate re-collection on the accident mitigation of 6 RMs was confirmed as shown in Fig. 7. The initial mass was maintained until the temperature of water reaches the saturation at 42.83 h. After 42.83 h, the

steep decrease in the mass was observed due to the boil-off of the emergency coolant in the cavities. As the steam mass fraction rapidly increased, the pressure and temperature increased in the plant building. Accordingly, the steam generation was accelerated because the latent heat of vaporization decreased.

However, the condensation heat transfer became effective from 43.33 h as the steam was generated and accumulated sufficiently in the plant building as shown in Fig. 7 (b). The condensation heat transfer increased due to the positive net steam generation. As the decay heat steadily decreased, the heat transfer by condensation exceeded the decay heat at 43.83 h. Consequently, the mass of the emergency coolant started to increase from 44 h because condensate is generated more than steam. As shown in Fig. 7 (a), the maximum consumption of the emergency coolant was estimated to be less than 0.2% of the initial mass. Thus, the flooding safety system can ensure indefinite grace period if the condensate is fully collected into the CP and cavities.

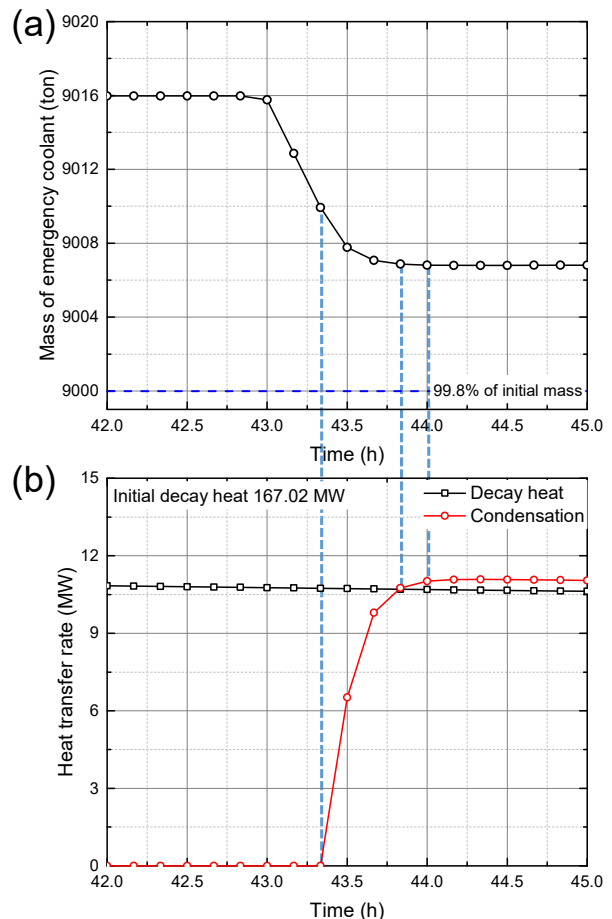


Fig. 7. Effects of full condensate re-collection on long-term safety (a) mass of emergency coolant, (b) heat transfer rate.

As mentioned before, the condensate is not expected to be fully collected due to the structures in the plant building. Accordingly, the effect of partial re-collection was investigated. Figure 8 shows that the effect of the collection ratio on the grace period is prominent for the

safety system. Because the grace period increases with the collection ratio, any practical method to enhance the collection ratio is needed for long-term coolability.

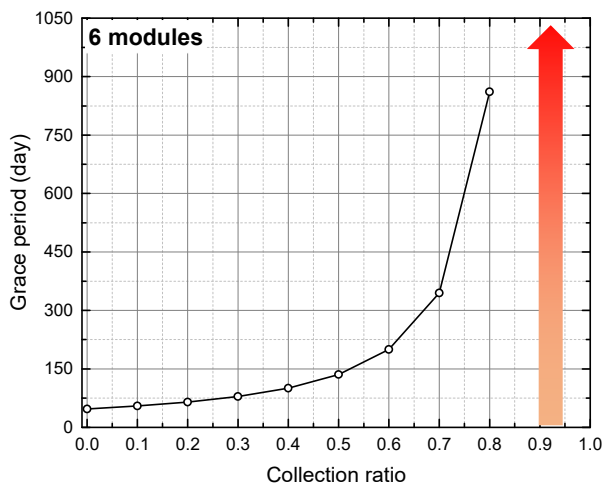


Fig. 8. Effect of the collection ratio on grace period.

### 5. Summary and Conclusion

In this study, the concept of the CFS for ATOM was proposed and the numerical analysis to confirm its feasibility was carried out. To sustain the water level in cavities, the boiled-off steam is condensed and collected into the CP, Aux. pools, and the cavities. The responses to the accidents such as LOCA, SBO, MSLB, and TLOFW were described. To confirm the feasibility of the safety system, the grace periods with and without condensate re-collection were investigated. The major outcomes can be summarized as follows:

- ✓ The grace periods were estimated as 43 days for the case of 6 RMs in accidents without condensate re-collection. Although it exceeded 3 days, generally required coping time for external response, additional methods are needed to enhance safety.
- ✓ The maximum consumption of the emergency coolant was estimated to be less than 0.2% of the initial mass with full re-collection of the condensate. Thus, the indefinite grace period can be ensured if the condensate is fully collected.
- ✓ However, adopting partial re-collection, the grace periods were limited. Nevertheless, the exponential increase in grace period with collection ratio was observed.

### Acknowledgments

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