Lumped Analysis of Effective Long-term Coolability by Using Flooding Safety System for Small Modular Reactors

Jae Hyung Park [a], Doyoung Shin [a], Taeseok Kim [a], Jeong Ik Lee[b], Yonghee Kim[b], Sung Joong Kim[a,c]*
[a] *Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*
[b] *Department of Nuclear and Quantum Engineering, Korea Advanced Insitute of Science and Technology., 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*
[c] *Institute of Nano Science and Technology, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*
[*] *Corresponding author: sungjkim@hanyang.ac.kr*

1. Introduction

In order to achieve the carbon-neutrality, small modular reactors (SMRs) have been globally highlighted thank to its advantages such as relatively lower initial capital cost, flexibility of power and site selection, and enhanced safety [1, 2]. Due to the extensive experiences of PWR-type reactors, the most feasible SMRs up to this time, such as NuScale and SMART, share the characteristics of Integrated PWR [3, 4].

The groundbreaking safety system including vacuumed containment vessel (CNV), submerged reactor modules (RMs) in a common pool (CP) was proposed by NuScale [3]. During loss of coolant accident (LOCA) or accidents involving overpressure of the primary system, the decay heat is removed by the condensation on the inner wall and boiling on the outer wall of the CNV. During accidents without discharge of coolant into the gap between the reactor pressure vessel (RPV) and CNV, the NuScale passive decay heat removal system transfers the decay heat from the steam generators (SGs) to the CP. Although the water in the CP is expected to be depleted after 30 days, the indefinite grace period can be secured by the air cooling alone since the decay heat at the time of coolant depletion is sufficiently reduced. However, an accident of a RM can affect all RMs because they are submerged in the same CP. In addition, management for activation of water in the CP during normal operation is a significant issue to be resolved.

Competing with the worldwide frontrunner in SMR development, Autonomous Transportable On-demand Reactor Module (ATOM), an advanced design of IPWR-type reactor, is currently under development in Republic of Korea [5]. The 6 ATOM modules each having thermal power of 450 MW_{th} have been envisioned to be installed in a plant building. The passive safety system concept of the NuScale is unarguable promising but, at the same time, it conflicts to deployment in terms of intellectual property ownership. In addition, assuming the infinite operation of the ATOM in conservative estimate, the decay heat is evaluated to exceed more than 280% of NuScale after 30 days even after a period longer than 30 days as shown in Fig. 1. To ensure long-term coolability of the ATOM, the water inventory of the CP has to be larger to delay the time to total depletion of the emergency coolant. Otherwise, an additional method is required to maintain the water surrounding the submerged RMs.

Thus, in this study the first-of-kind design of the ATOM safety system applicable for non-submerged RMs that can play a key role in improving the long-term cooling performance is proposed. The methods to mitigate the postulated accidents such as LOCA and station blackout (SBO) are presented. To investigate its long-term coolability, the algorithm for the numerical analysis was developed and realized through the MATLAB code.

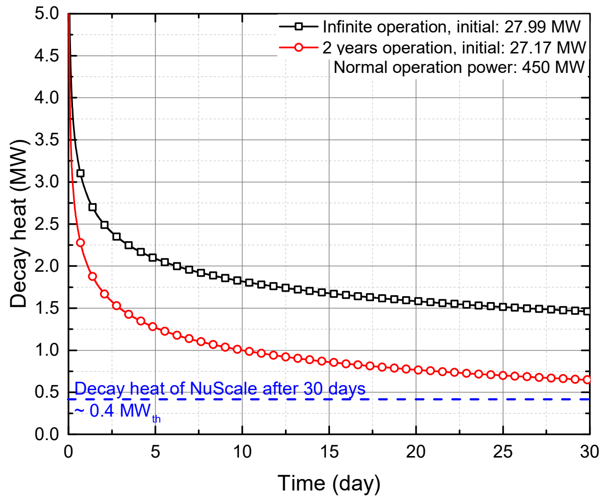

Fig. 1. Decay heat of a reactor module of the ATOM.

2. Concept of flooding safety system for ATOM

The RMs in the proposed safety system in this study are non-submerged during the normal operation. However, the dry cavities are flooded by cavity flooding system (CFS), which supplies the emergency coolant passively from the CP to the cavity during an accident. In this section, the geometric characteristics and methods to mitigate the postulated accidents are briefly discussed.

2.1. Geometry of flooding safety system

The main components of the proposed system are a CP, 6 auxiliary pools (Aux. pools), 6 separate dry cavities, and CFS, which is operated actively or passively 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.

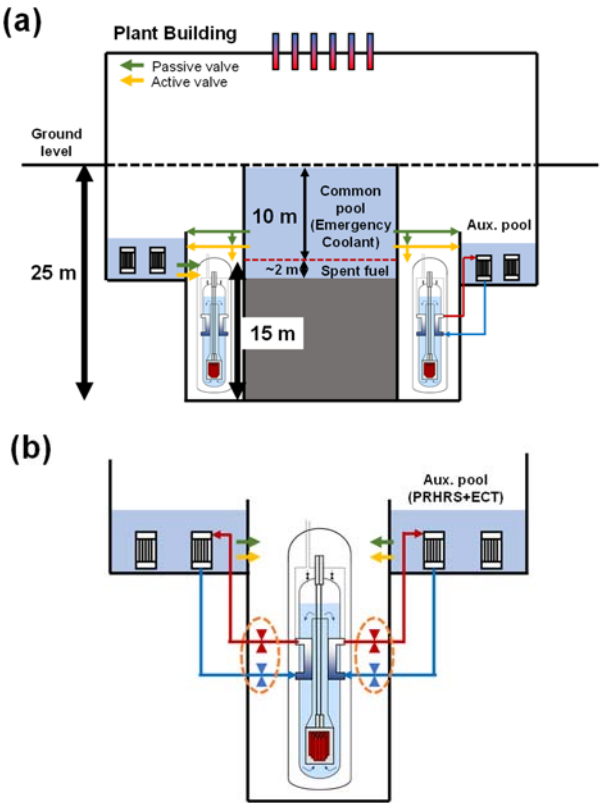

Fig. 2. Conceptual schematic of the CFS
(a) whole configuration, (b) PRHRS.

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.

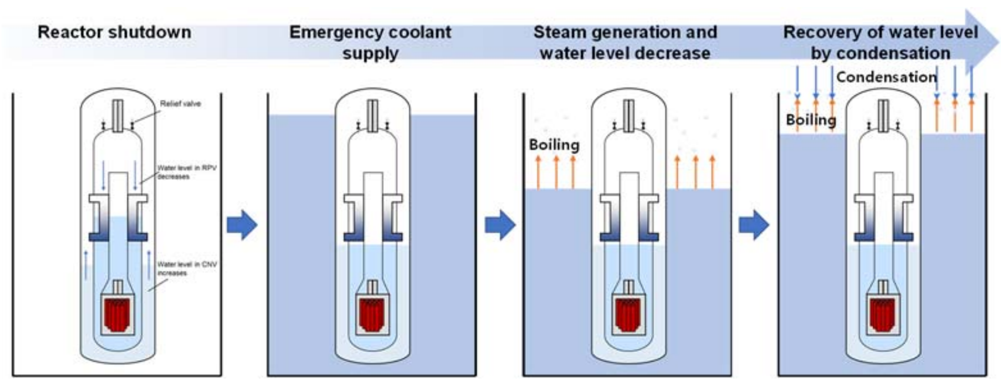

Fig. 3. Accident response processes during LOCA and SBO.

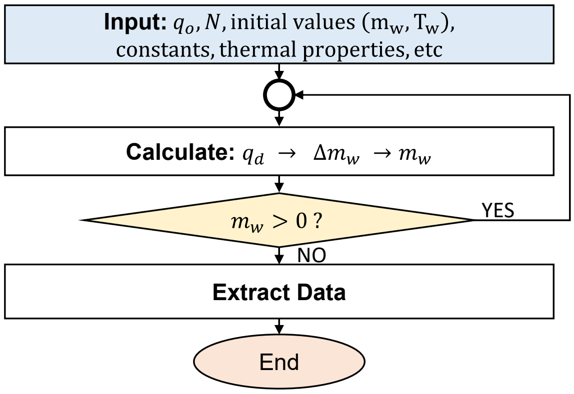

Fig. 4. Flow chart for the assessment of grace period without condensate re-collection.

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

Here, Q_d, Δm_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).

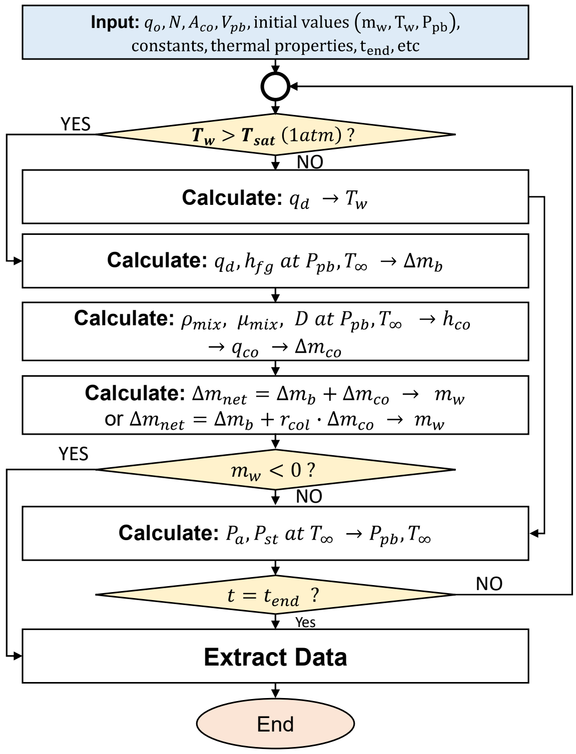

Fig. 5. Flow chart for the assessment of grace period with condensate re-collection.

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

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

Here, Q_{co}, $h_{fg,co}$, Δm_{net}, and Δm_{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%.

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

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 the plant building. In this study, the free volume and surface area of condenser were set to 11,830 m^3 and 260 m^2, 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.

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

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.

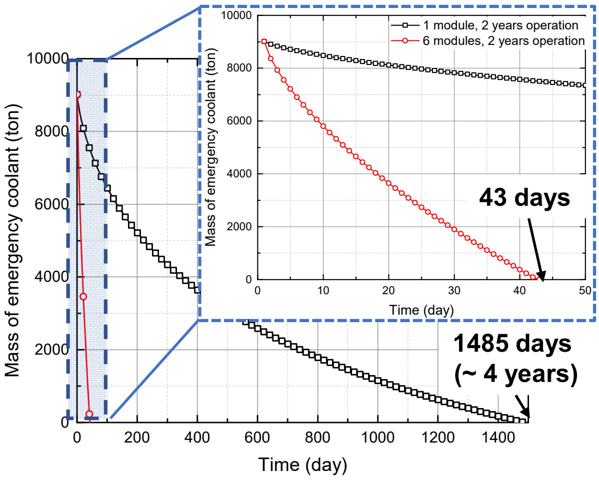

Fig. 6. Mass of the emergency coolant over time without condensate re-collection

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.

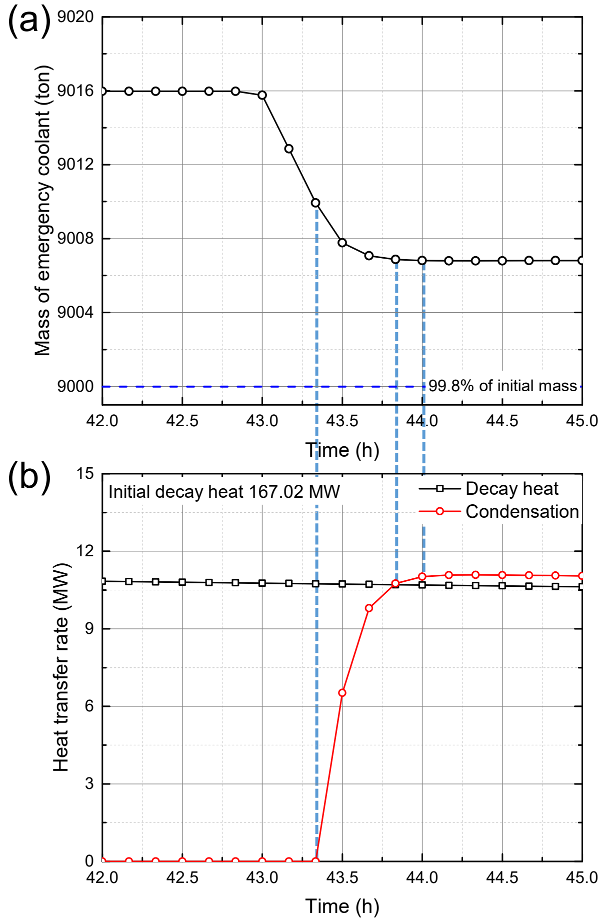

Fig. 7. Effects of full condensate re-collection on long-term safety (a) mass of emergency coolant, (b) heat transfer rate.

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.

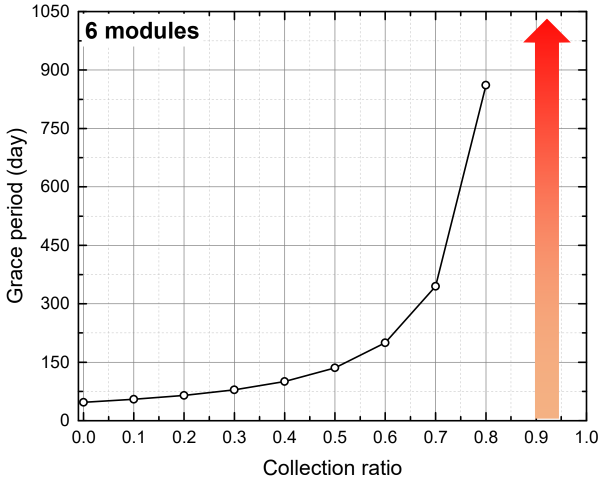

Fig. 8. Effect of the collection ratio on grace period.

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 exceed 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

This research was supported by the National Research Foundation of Korea (NRF), funded by the Ministry of Science, ICT, and Future Planning, Republic of Korea (No. NRF-2016R1A5A1013919 and No. NRF-2021M2D2A2076382).

REFERENCES

[1] J. Vujic, R.M. Bergmann, R. Skoda, M. Miletic, Small modular reactors: simpler, safer, cheaper?, Energy, Vol. 45, pp. 288-298, 2012.
[2] A. Lokhov, R. Cameron, V. Sozoniuk, OECD/NEA study on economics and market of small reactors, Nuclear Engineering and Technology, Vol. 45, pp. 701-706, 2013.
[3] J.N. Reyes Jr., NuScale plant safety in response to extreme events, Nuclear Technology, Vol. 178, pp. 153-163, 2012.
[4] K.H. Bae, H.C. Kim, M.H. Chang, S.K. Sim, Safety evaluation of the inherent and passive safety features of the smart design, Annals of Nuclear Energy, Vol. 28, pp. 333-349, 2001.
[5] X.H. Nguyen, C. Kim, Y. Kim, An advanced core design for a soluble-boron-free small modular reactor ATOM with centrally-shielded burnable absorber, Nuclear Engineering and Technology, Vol. 51, pp. 369-376, 2019.
[6] E.E. Lewis, Fundamentals of nuclear reactor physics, Chap. 1, Amsterdam: Elsevier/Academic Press., 2008.
[7] A. Dehbi, A generalized correlation for steam condensation rates in the presence of air under turbulent free convection, International Journal of Heat and Mass Transfer, Vol. 86, pp. 1-15, 2015.