MELCOR Analysis of Core Coolability by Flooding Safety System Applicable for i-SMR

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1. Introduction

Small Modular Systems (SMRs) have attracted considerable interest due to their inherent advantages over conventional large-scale Nuclear Power Plants (NPPs), including enhanced safety, a flexible power grid, reduced construction time, and remarkably smaller Emergency Planning Zone (EPZ) [1–6]. These can reduce the probability of Core Damage Frequency (CDF) and Large Early Release Frequency (LERF) substantially. In terms of radiological consequences, in turn, a higher safety can be achieved because the risk of radioactive material leakage is significantly lower.

Notwithstanding the superiority of SMRs, achieving comparable economic feasibility with conventional large-scale NPPs remains a critical issue to address, primarily due to small-scale power output per module. To attain higher economy, recent SMR designs have focused on increasing the module while maintaining the proposed higher safety, as demonstrated by several proposals, such as NuScale Power Module (NPM) (77 MWe), mPower (195 MWe), and WEC-SMR (225 MWe) [7–14].

Likewise, a Korean i-SMR (170 MWe) with a double Containment Vessel (CNV) geometry was proposed in 2021 and is under development. In case of Korean i-SMR, a several top-tier requirements were proposed, which include establishing the EPZ within the boundary of NPP site and targeting the CDF and LERF to be less than 1.0×10^{-9}/module-year and 1.0×10^{-10}/module-year, respectively. To meet these challenging goals, the development of innovative safety systems with a high level of reliability is being actively conducted.

In this regard, we proposed a Flooding Safety System (FSS) concept. The FSS is designed to function as an external CNV cooling mechanism activated under accident situations [15]. It aims to facilitate the condensation of steam generated during an accident progression and recirculate the condensate back into the active core region through an Emergency Recirculation Valves (ERVs) to maintain the core integrity. To evaluate the feasibility and effectiveness of the FSS, it is necessary to analyze its capability to secure core coolability through recirculation under accident environment.

To this end, this study focused on evaluating the extent to which water level in the core is sustained through recirculation under accident environment, utilizing MELCOR code for analysis. To perform MELCOR calculation, a 540 MWth i-SMR MELCOR input was developed. A conservative initial event was assumed where an Emergency Depressurization Valves (EDVs) are stuck open, leading to the discharge of coolant from primary system into the CNV.

2. Methodology

2.1. Development of i-SMR MELCOR input

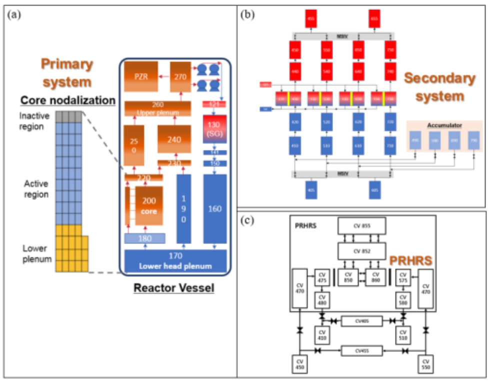

Fig 1. Nodalization of (a) primary system, (b) secondary system, and (c) PRHRS of MELCOR input for i-SMR

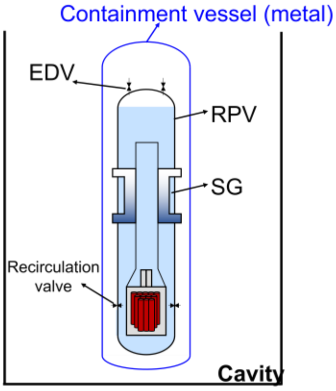

Fig 2. Schematic configuration of i-SMR module

Figure 1 illustrates the nodalization of primary system, secondary system, and Passive Residual Heat Removal System (PRHRS) in i-SMR MELCOR input [16, 17]. The PRHRS plays an important role in removing decay heat from the core under accident situation. In this study, however, it was assumed that the PRHRS is inoperable because this study focused on evaluating the potential for preventing core damage only with the FSS.

As illustrated in Fig. 2, the RPV is encased within a metal CNV. The EDV, located at the top of the RPV, functions as a passive depressurization mechanism for the primary system under accident environment. When the EDV automatically opens, the coolant is discharged through the valve and condensed on the inner wall of the CNV. To facilitate the introduction of the condensate into the active core, recirculation valves are installed at the upper side of core region. The recirculation valves are passively opened by the pressure difference under accident environment. In this manner, the coolant circulates through the RPV and CNV, maintaining the core water level without depletion.

Table 1 outlines the key design parameters of MELCOR steady-state calculation for 2,000 s. The parameters of interest include the core power, primary pressure, pressure of secondary system, mass flow rate of primary/secondary system, and inlet/outlet temperature of core region and steam generator. The stable calculation was achieved while maintaining core power of 540 MWth and primary pressure of 14.96 MPa.

Table I: Design parameters calculated with MELCOR steady-state calculation

Design parameter	MELCOR i-SMR
Core power [MWth]	540
Primary pressure [MPa]	14.96
Primary system mass flow rate [kg/s]	1,523.4
Core inlet temperature [℃]	267.8
Core outlet temperature [℃]	310.6
Secondary system mass flow rate [kg/s]	38.92
Secondary system pressure [MPa]	4.8
SG Primary inlet temperature [℃]	310.6
SG Primary outlet temperature [℃]	267.9
SG secondary inlet temperature [℃]	217.2
SG secondary outlet temperature [℃]	256.5

2.2. Accident progression

The initiating event was assumed to be stuck open of EDVs, in which the coolant in primary system is discharged into the CNV. Figure 3 illustrates the mass flow rate and energy discharge rate via the valves. The primary pressure decreases as steam is discharged, while the pressure inside the CNV gradually increases. The decay heat generation within the reactor core leads to the depletion of water and the generation of steam after 10,200 s, as shown in Fig. 4. To maintain the core integrity, therefore, the coolant discharged into the CNV needs to be promptly condensed on the inner wall of the CNV and recirculated into the core region prior to the depletion of water in the active core.

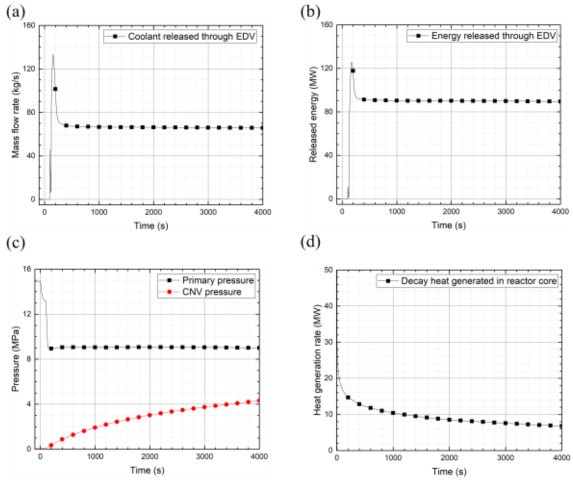

Fig 3. (a) Mass flow rate of coolant through EDV, (b) energy released through EDV, (c) pressures of primary system and CNV, and (d) decay heat generated within reactor core after EDV stuck open

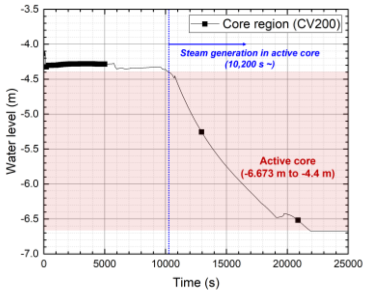

Fig 4. Water level in core region

2.3. Concept and modeling of FSS

Figure 5 illustrates the proposed concept of the FSS, which includes a Common Water Pool (CWP) with a capacity of 15,000 m^3 located at the center of plant building. In the event of an accident in a particular module, injection valves on the CWP are activated to fill the corresponding cavity. Therefore, external wall of the CNV is cooled by flooded water, which facilitates the condensation of steam within the CNV by increasing the rate of heat transfer through the wall. The rapid increase in water level within the CNV induces the passive opening of recirculation valves by differential head, which enables the coolant to flow back into the reactor core. Therefore, timely implementation of the FSS can be expected to prevent the active core from being exposed to the steam.

It was postulated that the operator’s action was initiated 5,000 s after the occurrence of initiating event. Hence, the FSS was modeled to operate since 5,000 s after the occurrence of initiating event as shown in Fig. 6. As a result, it was predicted that the whole CNV is submerged in water at 9,680 s, which is 4,680 s after the start of FSS operation.

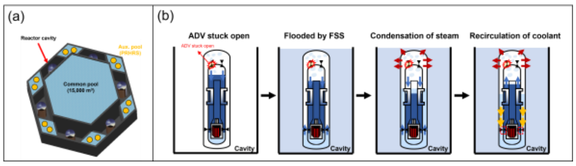

Fig 5. Concepts of (a) plant unit with CWP and (b) external CNV cooling after reactor cavity flooding by FSS

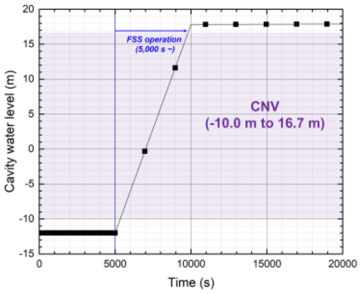

Fig 6. Increase in water level inside reactor cavity according to FSS operation

3. Result and discussion

Figure 7 illustrates the mass of water present in the RPV and CNV. The discharged steam was continuously condensed on the inner wall of the CNV, which increases the water within the CNV. The rate of condensation was predicted to start to decrease after 6,000 s due to the reduction in the heat transfer area resulting from the gradual rise in water level of the CNV. Nonetheless, the condensation occurred continuously due to the lower temperature of the CNV wall, as shown in Fig. 8. When the FSS was operated and the water level within the cavity increased, the outer wall of the CNV was cooled by the flooded water, leading to a reduction in the wall temperature. Consequently, this facilitated a rapid elevation in the water level within the CNV.

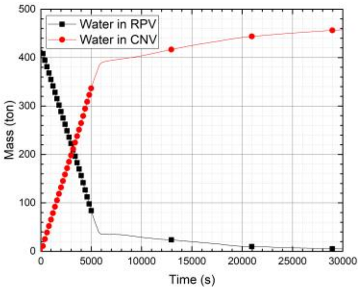

Fig 7. Mass of water present in RPV and CNV

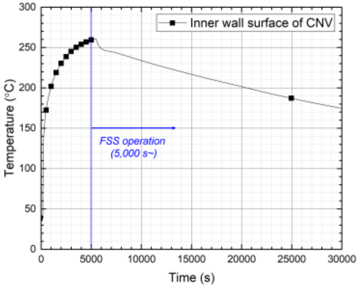

Fig 8. Temperature of inner wall surface of CNV

Figure 9 illustrates the water level within the CNV. It was observed that at 6,000 s, the water level reached a relatively high level of approximately 7.0 m compared to that in the core, corresponding to a differential head of more than 0.5 atm. Consequently, the flow of condensed coolant into the active core through the recirculation valves was triggered, as shown in Fig. 10. As a result, it prevented depletion of water in the active core region. Figure 11 illustrates the temperature of innermost fuel rods. It indicated that a stable temperature can be maintained owing to continuous cooling by the available coolant. Based on these observations, it could be concluded that implementation of the FSS can secure the core integrity effectively.

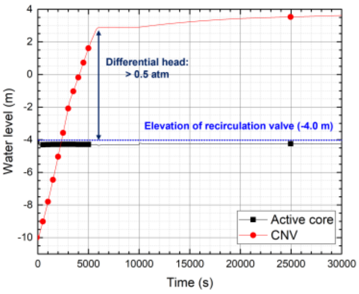

Fig 9. Increase in water level inside CNV

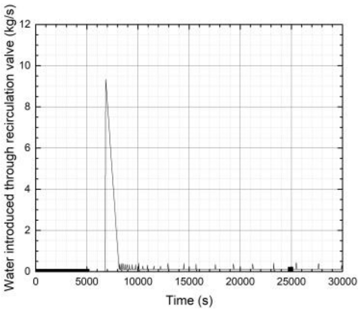

Fig 10. Mass flow rate of condensed water introduced via recirculation valves

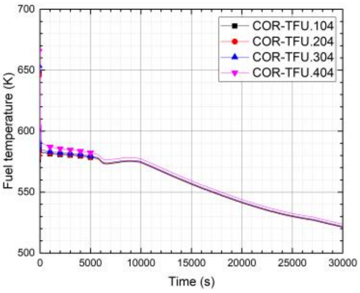

Fig 11. Temperature of innermost fuel rods inside active core

4. Conclusions

In this study, we proposed an innovative passive cooling mechanism by the FSS applicable for the Korean i-SMR with double CNV geometry and analyzed its feasibility by using MELCOR code simulation. To perform this, a MELCOR input for Korean i-SMR was developed. The initiating event was assumed to be stuck open of EDVs, in which the coolant in primary system was discharged into the CNV. The major findings and future works in this study can be summarized as follows.

(1) The i-SMR was successfully modeled in the MELCOR 2.1 code, and a reasonable steady-state calculation results were obtained.
(2) The FSS was modeled to operate since 5,000 s after the occurrence of initiating event. As outer wall of the CNV was cooled by flooded water, steam discharged through the EDV was condensed continuously at the inner wall surface of the CNV.
(3) Accordingly, the water level inside the CNV exceeded that inside the active core by more than 7.0 m before the active core is exposed to steam, resulting in a differential head of more than 0.5 atm. Consequently, the flow of condensed coolant into the active core through the recirculation valves was triggered.
(4) Based on this successful recirculation, the water in the active core could avoid the depletion. As a result, the fuel temperature did not increase despite the continuous generation of decay heat. This indicated that the core integrity could be secured through the external CNV cooling by the FSS.
(5) To analyze the complex thermal hydraulic phenomena in more detail, additional precise analysis through Computational Fluid Dynamics (CFD) code will be conducted in future research.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT: Ministry of Science and ICT) (No. 2022M2D2A1A02061334 and RS-2022-00144202).

REFERENCES

[1] What are Small Modular Reactors (SMRs)? (2021, November). IAEA, https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs
[2] IAEA, “Advances in Small Modular Reactor Technology developments,” (2020).
[3] Subki, M.H. Update on International SMR Development and Deployment Activities. In Proceedings of the IAEA Technical Meeting on Roadmap for SMR Deployment, Vienna, Austria, 12 October 2015.
[4] Nuclear Energy Agency. Current Status, Technical Feasibility and Economics of Small Nuclear Reactors; Organisation of Economic Cooperation and Development: Paris, France, 2011.
[5] J. Vujic, R.M. Bergmann, R. Skoda, M. Miletic, Small modular reactors: simpler, safer, cheaper?, Energy, Vol. 45, pp. 288-298, 2012.
[6] 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.
[7] Integral PWR-Type Small Modular Reactor Developmental Status, Design Characteristics and Passive Features: A Review
[8] Chelsea C. et al., “Improvements in SMR Modular Construction through Supply Chain Optimization and Lessons Learned,” (2017).
[9] Ingersoll et al., NuScale small modular reactor for Co-generation of electricity and water,” Desalination, 340(1), pp. 84-93, (2014).
[10] Martin, Robert & Williams, E.S. & Williams, J.G.. (2013). Thermal-hydraulic design of the B&W mPOWER™ SMR - 2013 ANS Meeting. Transactions of the American Nuclear Society. 109. 2269-2272.
[11] International Atomic Energy Agency. Advances in Small Modular Reactor Technology Developments; A Supplement to: Advanced Reactors Information System 2018 Edition; IAEA: Vienna, Austria, 2018.
[12] NuScale Power, LLC. NuScale plant design overview. United States Nuclear Regulatory Commmission; NuScale Power, LLC.: Washington, DC, USA, 2012.
[13] NuScale Power, L.L.C. NuScale Standard Plant Design Certification Application. Chapter Six: Engineered Safety Features; PART 2-TIER 2; NuScale Power, LLC.: Washington, DC, USA, 2016.
[14] NuScale Power, L.L.C. NuScale Standard Plant Design Certification Application. Chapter Five: Reactor Coolant System and Connecting Systems; PART 2-TIER 2; NuScale Power, LLC.: Washington, DC, USA, 2016
[15] Park et al., “Lumped analysis of effective long-term coolability by using Flooding Safety System for small modular reacotrs,” Transactions of the Korean Nuclear Society Autumn Meeting, Changwon, Korea
[16] L.L. Humphries, R.K. Cole, D.L. Louie, V.G. Figueroa, M. F. Y. (2015). MELCOR Reference Manual
[17] L.L. Humphries, R.K. Cole, D.L. Louie, V.G. Figueroa, M. F. Y. (2015). MELCOR Users Guide