Investigation for Effective Flow Path Designed for Flooding Safety System by Using MELCOR code

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1. Introduction

NuScale power module (NPM), the leading design of small modular reactor (SMR), features an innovative passive safety system capable of achieving an indefinite grace period [1]. The NPM proposes a double vessel structure, in which a reactor pressure vessel (RPV) is encapsulated in the containment vessel (CNV). For a standard design, 12 reactor modules (RMs) are immersed in a common pool (CP) for passive decay heat removal from the core during an accident. However, the passive safety system of the NPM is expected to exhibit several limitations such as limited power rating hindering the achievement of the economy and heat loss during normal operation due to permanent immersion of passive safety system.

To overcome such limitations, a flooding safety system (FSS), the passive safety system for an advanced SMR designs with the double vessel structure, was proposed [2]. The FSS shown in Fig. 1 is composed of CP, cavities, auxiliary pools, passive residual heat removal system (PRHRS), and passive air-cooled condensation system. The CP stores a large inventory of emergency coolant sufficient to fill all the cavities and spent fuels. During a loss of coolant accident (LOCA), the energetic steam is released into the CNV, while emergency coolant is supplied to the cavity containing the RM during an accident through the flooding system which is operated by integrated circuit (IC) logic. The steam is condensed on the cold inner wall of the CNV. As the wall is heated by the steam, condensation performance can be deteriorated due to the wall temperature rise. Eventually, however, the CNV can be cooled by the emergency coolant supplied into the cavity.

During the accidents initiated by an abrupt degradation of heat transfer and cooling performance of the steam generators (SGs), the PRHRS is actuated, and the heat is removed from the SGs to the PRHRS heat exchangers installed in the auxiliary pools. As the water in the cavity evaporates, the steam is diffused to the upper side of the plant building and condensed on the passive condenser installed on the ceiling. Since the condenser is positioned right above the CP, the generated condensate falls and re-collected into the CP. Subsequently, the re-collected water can be re-supplied into the cavity or auxiliary pool. Consequently, the emergency coolant supply capability can be sustained for an extended period.

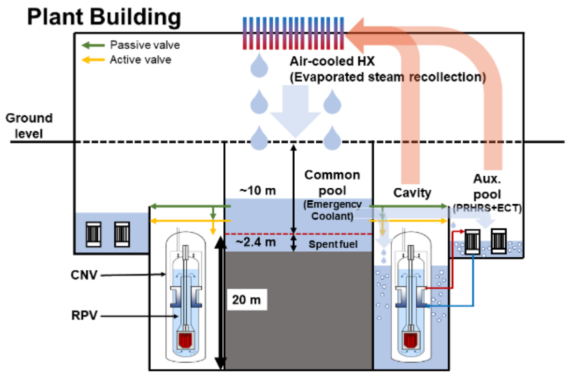

Fig. 1. A conceptual schematic of FSS.

In the previous studies, the long-term coolability enhancement and required flow area were investigated through numerical analysis by using in-house code and MELCOR code [2, 3]. However, the previous results were insufficient in determining the detailed state of the reactor modules. In addition, the time was limited to supply the emergency coolant into the cavities because the accident phenomena were analyzed without the FSS which means, accident analysis with the cavity flooding was not conducted. In other words, the more practical cases could not be considered although the approximates were suggested.

Thus, the objective of this study is to investigate the required cavity flooding time to prevent transition to severe accident including core damage and the effect of the flow area of the flooding system on the flooding time and subsequently, on the accident mitigation. Numerical analysis was carried out to simulate base case accident with and without the FSS by using MELCOR 2.2.9541 code.

2. Methodology

2.1. A reference reactor

Autonomous Transportable On-demand reactor Module (ATOM) SMR with thermal power of 330 MWt was selected as the reference reactor [4]. The ATOM is under development as an advanced design of integral pressurized water reactor (IPWR) with innovative SMR technologies such as autonomous control, advanced materials, long refueling cycle, to mention a few. Major components such as core, pressurizer, steam generators, and reactor coolant pumps are integrated in an RPV. ATOM also adopted the double vessel structure. The primary system of the RPV is pressurized to 14.6 MPa while the gap volume between the RPV and CNV is filled with 0.1 MPa dry non-condensable gas for the thermal insulation and hydrogen inflammability control. The ATOM includes an automatic depressurization system (ADS) with three ventilation valves installed on the top of the RPV to depressurize the RPV and two recirculation valves for the recirculation between the RPV and the CNV during an accident. Six ATOM RMs are designed to be installed in the plant building.

2.2. MELCOR modelling

An input model of the 330 MWt ATOM was used in the MELCOR accident simulation and analysis of the FSS under a postulated accident scenario. The nodalization of the MELCOR input model is shown in Fig. 2. Main components of the model are as follows; core, steam generator, downcomer, pressurizer, reactor coolant pump (RCP), CNV, CP, and cavity. The ADS valves were modeled as three flow paths connecting the pressurizer and CNV. In addition, recirculation valves were modeled as two flow paths connecting the downcomer and CNV. The height of the CP and cavity was set as 10 m and 20 m, respectively. The heat structure between the CNV and cavity was divided into 40 heat structures, 20 each for lower section and upper section of the CNV. A CNV rupture was assumed to occur at high CNV pressure circumstances, specifically at 8.0 MPa.

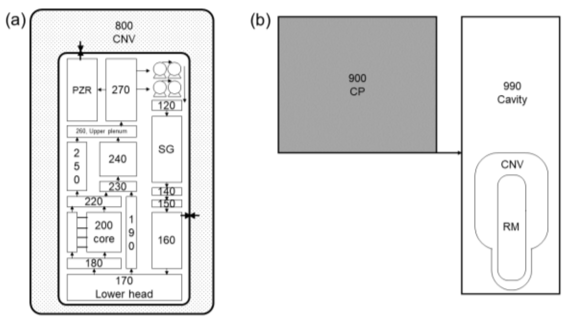

Fig. 2. MELCOR nodalization (a) reactor pressure vessel and containment vessel of ATOM, (b) flooding safety system.

2.3. MELCOR accident scenario

An ADS malfunction accident scenario was introduced for the MELCOR accident simulation. During the normal operation, one of the ADS valves was assumed to be opened undesirably. The scenario was chosen to evaluate coolability using the cavity water only. Thus, the PRHRS, whose heat removal analysis was previously conducted, was excluded [5]. A base case accident scenario was simulated to determine the required flooding time. The effect of various flooding valve flow area on the flooding time and accident mitigation was investigated by using the MELCOR code.

3. Result and discussion

Steady-state operation parameters were obtained from the MELCOR calculation by using the input model. Major operating parameters of the ATOM input models were summarized in Table I.

Table I: MELCOR input model steady-state parameters

Parameter	Steady-state value
Core thermal power, MWt	330
Primary system pressure, MPa	14.6
Core inlet temperature, ^{o}C	270.3
Core outlet temperature, ^{o}C	311.1
Core inlet mass flow rate, kg/s	1,528.6
SG steam pressure, MPa	4.3
Feed water inlet temperature, ^{o}C	157.6
SG outlet steam temperature, ^{o}C	255.3
Feed water flow rate, kg/s	155.7

3.1. Base case analysis

MELCOR accident simulation was carried out for the base case excluding the flooding of the cavity. Table II shows severe accident sequences of the base case accident.

TABLE II: Accident sequence

Event	Time (sec)	Time (hour)
ADS malfunction	100	0.028
Reactor, RCP, main feedwater trip	102	0.028
Recirculation start	4,591	1.28
CNV rupture	8,000	2.22
Oxidation start	9,360	2.6
Fuel gap release	9,443	2.62
Core support plate failure start	10,256	2.85
Core bottom dryout	10,400	2.89
Relocation to lower plenum	11,680	3.24

The accident was initiated by the accidental opening of one of the ADS valves, which caused a decrease in RPV pressure and an increase in CNV pressure due to the steam release into the CNV as shown in Fig, 3. Heat transfer through the CNV wall was the only available decay heat removal mechanism from the system. However, as shown in Fig. 4, the absence of a heat sink caused an increase in the CNV wall temperature, which, in turn, deteriorated the condensation rate on the CNV wall and increased the steam accumulation in the CNV. This eventually led to the rupture of the CNV. On the other hand, there was sufficient CNV water level for recirculation to be activated, and the core remained submerged before the CNV rupture as shown in Fig. 5.

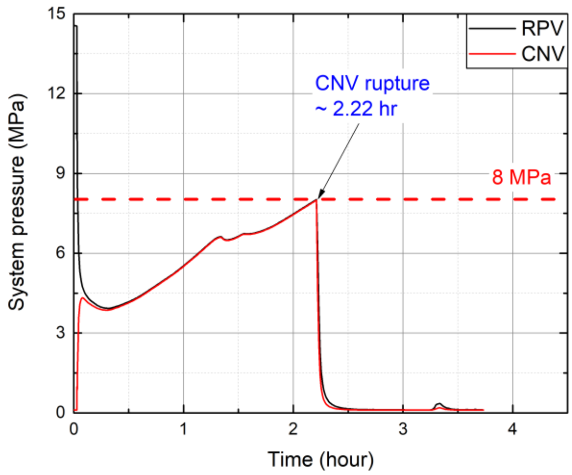

Fig. 3. System pressure of RPV and CNV.

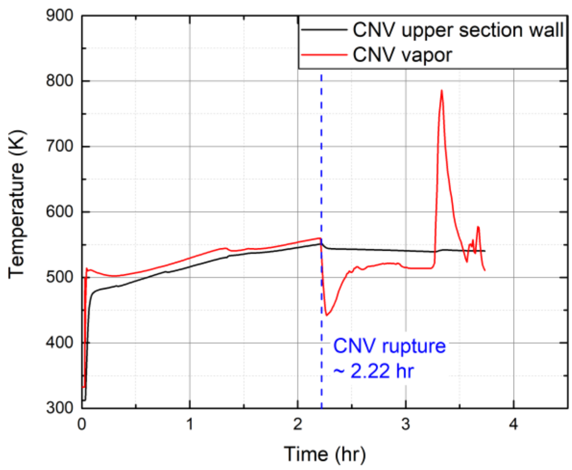

Fig. 4. CNV inner wall averaged surface temperature and CNV vapor temperature.

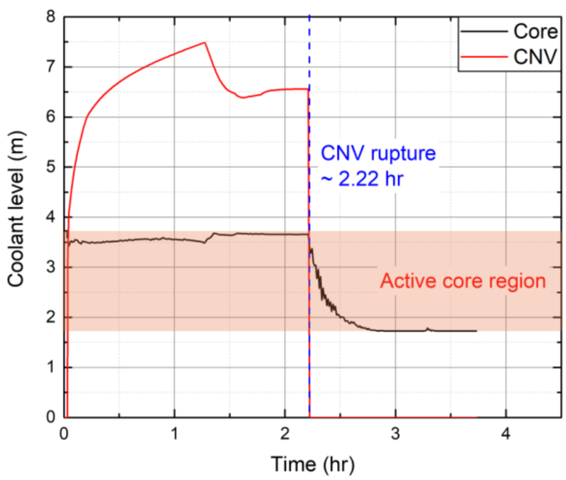

Fig. 5. Coolant level of core and CNV.

After the CNV rupture, the pressure and water level in both the CNV and RPV significantly decreased causing the fuel temperature to rise. The cladding started to oxidize and the core began to heat up rapidly. Eventually, the core became dried and the temperature increased up to the melting point. Moreover, radionuclides were released out of the core, and dispersed throughout the cavity and the plant building.

Obviously, CNV rupture was the most critical event to the reactor integrity and insufficient condensation on the CNV inner wall due to the absence of heat sink was the very first reason of the event. Fig. 6 shows that the degrading condensation performance on the CNV wall increased the steam accumulation in the CNV, which was represented by the difference between steam condensation and release. Thus, the preferential objective of cavity flooding is to provide adequate heat sink to the CNV wall. To enhance the condensation performance on the CNV inner wall, the wall exposed to the steam should be cooled under any circumstances. Thus, it is necessary to secure the cavity water level higher than the CNV water level prior to the CNV rupture. However, simply having a higher cavity water level does not guarantee successful mitigation as the steam condensation rate must exceed the steam release rate for the effective CNV depressurization.

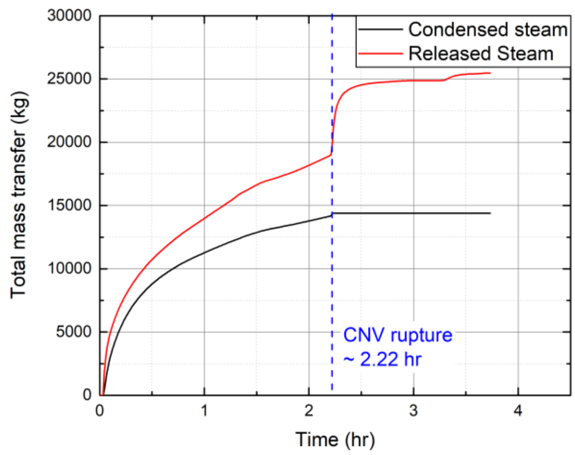

Fig. 6. Total mass of released steam into the CNV and condensed steam on the CNV wall.

3.2. Effect of flooding time on accident mitigation

To examine the effect of flooding time, five MELCOR accident simulations were carried out. The simulation matrix was presented in Table I and the results of flooding time with flow area are shown in Table III. As shown in Fig. 7, CNV pressure showed similar behavior across all cases during the early stages of the accident due to insufficient flooding. However, pressure difference between cases increased as the cavity is flooded. The CNV pressure gradually decreased with peak pressure lower than 8.0 MPa except the 0.006 m^2 case where the high CNV pressure caused the CNV rupture. In 0.006 m^2 case, the upper CNV wall remained uncooled, eventually leading to CNV rupture. However, the cavity water could cool the CNV water as shown in Fig. 8. Before the CNV rupture, CNV water temperature of 0.006 m^2 case decreased while the base case temperature increased and became equal after the rupture. The cooling of the CNV water enhanced condensation on the interface of the water and steam delaying CNV rupture by around 10 minutes.

Table III: Flooding time with valve area

Valve flow area (m^2)	**0.006**	**0.008**	**0.01**	**0.02**	**0.03**
Equivalent diameter (m)	**0.087**	**0.1**	**0.113**	**0.16**	**0.195**
6.6 m flooding time (hour)	2.30	1.72	1.38	0.69	0.46
Fully flooding time (hour)	11.21	8.39	6.69	3.32	2.20

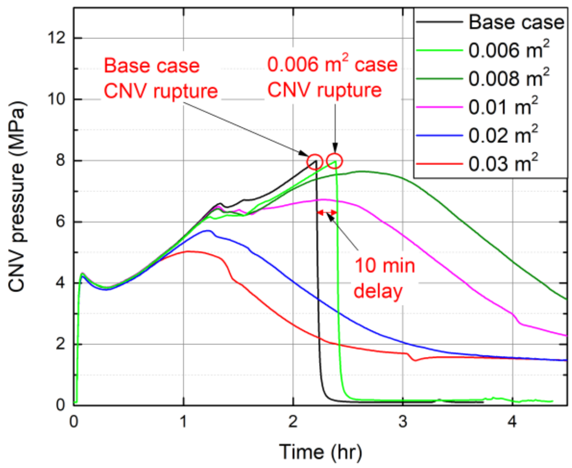

Fig. 7. CNV pressure in flooding cases and base case.

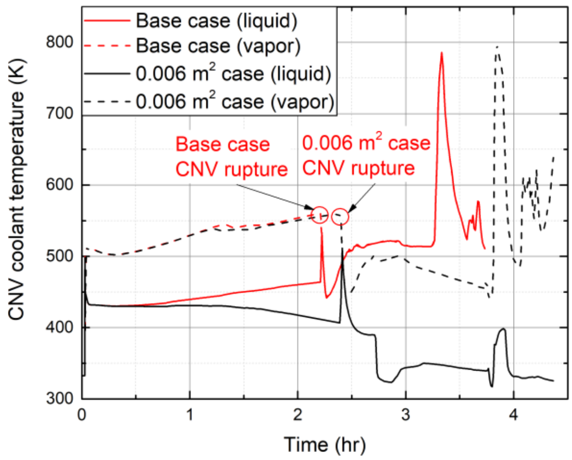

Fig. 8. CNV coolant temperature in 0.006 m^2 flooding case and base case.

The activation time of recirculation valves showed little difference across all cases, including the base case. The core water level was sustained, and core uncovery was not observed in cases within valve flow area from 0.03 m^2 to 0.008 m^2 as shown in Fig. 9. The reactor fuel temperature remained low enough. However, in case of the 0.006 m^2 valve, the core water level was not sustained after the CNV rupture, and the reactor core was severely damaged after the core dry-out similar to the base case result. Thus, it can be concluded that flooding with valve flow areas between 0.03 m^2 to 0.008 m^2 was effective in sustaining the RM integrity while flooding with the 0.006 m^2 valve was inadequate in preventing the RM damage.

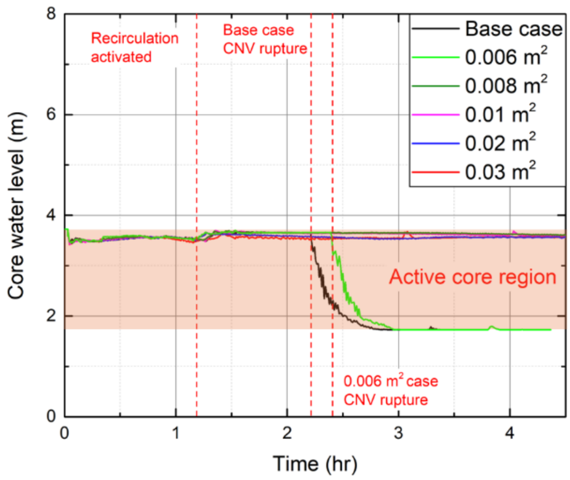

Fig. 9. Water level of CNV and core in flooding case and base case.

4. Conclusion

This paper conducted a feasibility analysis of FSS using the MELCOR code to determine the required flooding time to prevent RM damage during the early stage of the postulated accident. Effect of the flooding valve area on the flooding time and accident mitigation was assessed by MELCOR code. Specific results of the study were summarized as follows.

✓ The CNV rupture caused by overpressure of CNV led to the core dryout and severe damage of the reactor core resulting in the release of radionuclides outside the RM.

✓ To depressurize the CNV, condensation rate on the CNV inner wall should overcome the steam release rate into the CNV by flooding the cavity sufficiently higher than the CNV water level.

✓ The flooding case simulation results indicated that the cases with flooding valve flow areas ranging from 0.03 to 0.008 m^2 were able to maintain the RM integrity successfully.

✓ However, 0.006 m^2 case failed in mitigating the accident due to the overpressure of the CNV accompanied by CNV rupture event.

From the results, the CNV peak pressure can increase as the flooding was delayed. To ensure the RM integrity and safety, more detailed investigation on the peak pressure is needed. Since the CNV design pressure is also related to manufacturing, the CNV size will be determined under the affordable design. While the valve with flow area of 0.008 m^2 case may be acceptable based on the MELCOR calculations, its flooding time needs to be considered as a marginal value. In addition, to secure multiplicity in the safety system, multiple flooding valves are required to be installed for each cavity.

Acknowledgments

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