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Sensitivity Analysis for Metal Containment Vessel Wall Thickness to Accommodate Flooding Safety System using MELCOR Code.

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1. Introduction

Small modular reactors (SMRs) are expected to be one of the key nuclear reactor types for future energy supply system. Developments of SMRs are extensively pursued worldwide owing to their numerous advantages, such as compatibility with renewable energy sources, versatile applications, and enhanced safety features [1-3]. Especially, SMRs are beneficial in adopting passive safety systems owing to their characteristics such as modular design, and low thermal power. Passive characteristics for the safety systems are highly preferable as they do not rely on the electricity and operator action.

Flooding safety system (FSS) (patent no. 10-2534650) is an innovative concept of passive safety system for SMRs with metal containment vessel (MCV) [4, 5]. The FSS envelopes reactor modules (RMs) in separated dry cavities (SDCs) during normal operation. When an accident occurs, the FSS supplies emergency coolant to the cavity of the RM by valve operation. Subsequently, the emergency coolant forms a water pool and absorbs the decay heat from the RM. The emergency coolant is stored in a common pool (CP) and supplied to the cavity through flooding valves which are activated in both active and passive mechanisms.

As the emergency coolant is supplied after the control rod insertion by reactor trip signal, the initial state of the reactor has less coolability for the removal of the decay heat due to the absence of the reactor cavity pool. In addition, the probability of the delayed flooding presences due to the response time and potential partial malfunction of the flooding valves. To provide the time to secure sufficient heat sink, the RM has to maintain its integrity. At that stage, the MCV structure plays an important role as a temporary heat sink for the heat removal. As the decay heat generated from the core evaporates the coolant in the RPV, the steam is condensed on the MCV inner surface transferring the heat to the MCV structure.

The mass of the MCV structure and its heat capacity are determined by the thickness of the structure given the same size of the MCV including the inner diameter. The increase of the MCV wall thickness and the structure heat capacity extends the period that the RM can sustain its integrity. However, the increased MCV wall leads to the higher conduction heat transfer resistance of the wall, deteriorating the heat removal rate through the MCV structure after flooding. Thus, the comprehensive effects of the MCV wall thickness on the accident management need to be assessed during the design process.

In this study, we conducted a sensitivity analysis of the MCV wall thickness to accommodate the coolability of the MCV structure and allowable MCV peak pressure and end pressure. MELCOR code version 2.2.r2023.0 was used to simulate the reactor emergency depressurization valve (EDV) stuck open accident scenario.

2. Methodology

2.1. Reference reactor

The Natural circulation SMR (NC-SMR) with thermal power rating of 330 MWt was used as a reference reactor of the study. Fig. 1 shows a conceptual design of the reactor. The NC-SMR was conceptualized based on an integrated pressurized water reactor (IPWR), whose main components such as core, pressurizer, steam generator (SG) are integrated into a reactor pressure vessel (RPV). The NC-SMR utilizes natural buoyancy force to circulate primary coolant from the core to SG. The height of the reactor, approximately 28 meters, was determined to provide sufficient driving force for the primary coolant circulation. As the natural circulation is driven by the density difference between the hot and cold coolant, temperature difference between the inlet and outlet of the core is relatively higher compared to the forced circulation reactors.

The NC-SMR incorporates the MCV concept, which encapsulates the RPV. The RPV operates at 15.5 MPa, while the MCV maintains a pressure of 0.1 bar (weak vacuum). The NC-SMR includes emergency core cooling system (ECCS) consisting of EDVs on the top of the pressurizer and emergency recirculation valves (ERVs) positioned between the downcomer and the MCV. The EDVs and ERVs connect the RPV with the MCV to recirculate the primary coolant and to remove the decay heat out of the RM during an accident. The EDVs and ERVs are designed to passively open when the pressure difference between the valves decreases to a certain pre-set threshold pressure.

2.2. Description of flooding safety system

FSS is an innovative passive safety system for SMRs with MCV. Fig. 2 shows the conceptual design of the FSS. During normal operation, the FSS stores emergency coolant in the CP, which also acts as a spent fuel pool. The volume of the CP is 9,408 m^3 which is enough to fill out all six cavities. Alongside the CP, six separated dry cavities and six RMs are located. When an accident occurs in a certain RM, the flooding valve of the CP is opened, selectively suppling the emergency coolant to the cavity of the RM. Next to each cavity, an auxiliary pool is located to provide heat sink for the passive residual heat removal system (PRHRS), a passive safety system to remove decay heat through the SG. In addition, a passive air-cooled condensation system is installed on the ceiling of the plant building to recollect the evaporated steam from the cavity and auxiliary pool.

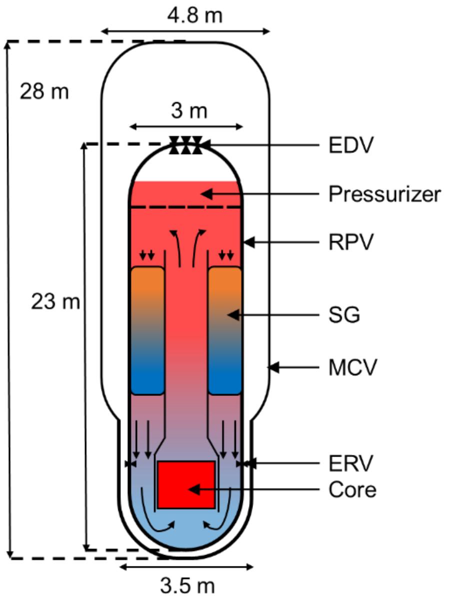

Fig 1. A conceptual schematic of NC-SMR

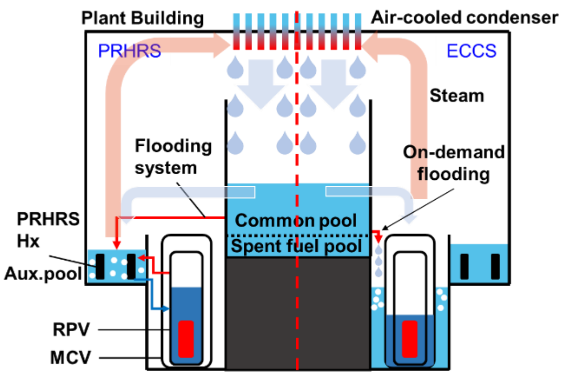

Fig 2. A conceptual schematic of FSS

2.3. MELCOR code input model

A MELCOR code input model of the NC-SMR with FSS was developed to simulate the RM in an accident. Nodalization of the input model is shown in Fig. 3. Main components of the NC-SMR such as core, SG, pressurizer were included. A pressurizer heater with PID algorithm power control was installed. The EDVs and ERVs were set to be opened when the pressure difference between the valve is lower than 7.6 MPa and 0.2 MPa, respectively. MCV wall heat structures were modeled to calculate heat transfer between the MCV and the cavity. The MCV heat structures were divided into 29 axial nodes for detailed simulation of the heat transfer with the varying cavity water level. Initial MCV inner atmosphere condition was set as 0.1 bar dry air condition. A flow path between the MCV and the cavity was set to simulate the MCV damage and leakage resulting from the MCV overpressure. The design pressure of the MCV was set to be 8.0 MPa, referenced from the NuScale power module [6]. The FSS part modeled the plant building including the CP, cavities, and the condenser. Flooding valves were set to open when the reactor trip signal is generated with a specified delay time.

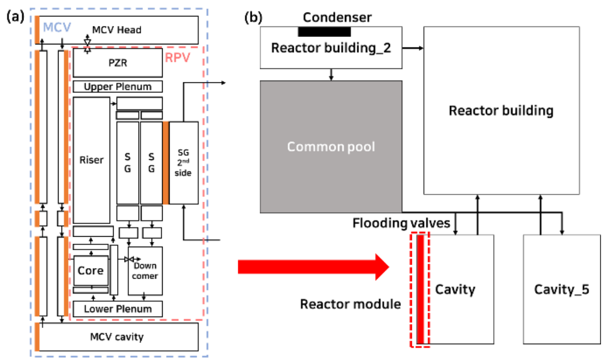

Fig 3. MELCOR nodalization (a) NC-SMR, (b) FSS

2.4. MELCOR accident scenario

An EDV stuck open accident was postulated for the MELCOR accident simulation. The scenario initiates with an undesirable opening of an EDV during normal operation. The event results in the release of the hot steam from the pressurizer to the MCV, leading to a rapid equalization of the pressure between the RPV and the MCV. The released steam is condensed on the MCV inner wall surface, transferring the heat to the MCV wall. Therefore, the major accident management strategy for this scenario is flooding the cavity. In this study, activation of the PRHRS was not considered. The flooding was assumed to start an hour after the reactor trip, considering the response time. The estimated time for fully flooding the cavity is approximately 2.36 hours after the accident.

2.5. Numerical modeling used to simulate major phenomenon

Major heat transfer mechanisms at MCV are condensation on the inner surface and nucleate boiling on the outer surface. Eq. (1) to Eq. (3) represent the condensation model used in the MELCOR code. The Sherwood number (Sh) is calculated from the Nusselt number (Nu), Schmidt number (Sc), and Prandtl number (Pr). Using the Sherwood number, mass transfer coefficient, h_D can be determined. Subsequently, condensation mass flux $(\dot{m}_C)$ is calculated. The heat flux due to the condensation can be derived by multiplying the condensation mass flux and specific condensation enthalpy change. On the other hand, nucleate boiling heat flux $\left(q_{nb}^{"}\right)$ can be calculated from Rohsenow relation shown in Eq. (4) [7].

$$Sh = \frac{h_D L_C}{D} = Nu Sc^{1/3} Pr^{-1/3} \quad (1)$$

$$Sc = \frac{\mu}{\rho D} \quad (2)$$

$$\dot{m}_C = h_D \rho_V \ln(P_{tot} - P_{sur}/P_{tot} - P_{steam}) \quad (3)$$

$$\left[\frac{c_{pl}\left(T_{surf} - T_{sat}\right)}{h_{fg}}\right] = 0.013\left[\frac{q_{nb}^{"}}{\mu h_{fg}}\left(\frac{\sigma}{g(\rho_l - \rho_V)}\right)^{1/2}\right]^n Pr \quad (4)$$

3. Result and discussion

3.1. NC-SMR steady state simulation

Before conducting the accident analysis, steady-state operation parameters of the NC-SMR MELCOR input model were obtained. Specific parameters were shown in the Table I.

Table I: MELCOR input model steady-state parameters

Parameter	Steady-state value
Core thermal power, MWt	330.06
Primary system pressure, MPa	15.0
Core inlet temperature, ℃	254.82
Core outlet temperature, ℃	327.24
Core inlet mass flow rate, kg/s	848.60
SG steam pressure, MPa	4.3
Feed water inlet temperature, ℃	150.03
SG outlet steam temperature, ℃	297.89
Feed water flow rate, kg/s	141.63
MCV inner temperature, ℃	240.94
Enthalpy increase in core, MW	330.06
Enthalpy decrease in SG, MW	330.08

3.2. NC-SMR MCV wall thickness sensitivity analysis

In this section, MELCOR accident simulations to analyze the sensitivity of the MCV wall thickness are discussed. Table II shows a simulation matrix for the sensitivity analysis and resulting MCV total mass and outer surface heat transfer area. A reference MCV wall thickness of 7.6 cm was selected from the NuScale power module [6].

Table II: MELCOR simulation matrix

Sensitivity parameter	Value					
MCV wall thickness (cm)	5	6	7	8	9	10
Total MCV mass (ton)	45.3	54.5	63.7	72.9	82.2	91.5
MCV outer heat transfer area (m^2)	212.9	213.7	214.5	215.3	216.2	217.0

Total six simulation results were calculated. Fig. 4 shows the MCV pressure for each case and the Table III shows the MCV peak pressure and pressure at 5 hours after the accident.

As the accident initiated, the MCV pressure began to rise due to the steam release from the RPV. The pressure continued to increase until about 1.3 hour, even after start of the flooding at 1 hour, due to the continuous evaporation of the primary coolant by the decay heat from the core. The pressure increase was more pronounced in the thinner wall cases compared to the thicker cases. The MCV pressure in the 5 cm case reached to the MCV design pressure, resulting in the MCV damage. On the other hand, the thicker MCV wall cases showed lower MCV peak pressure owing to the higher MCV structure heat capacity. As shown in Fig. 5, the thicker MCV wall cases showed the lower MCV wall temperatures during the early phase of the accident. Moreover, the temperature increase was not proportional to the mass of the MCV structure, which means thicker MCV absorbed more thermal energy compared to thin MCV. These results indicate that the effect of the increase in heat capacity resulting from the thicker MCV wall was significant in suppressing the MCV pressure increase. Therefore, a thicker MCV wall could be beneficial in terms of safety margin of the MCV design pressure.

Table III: MCV peak pressure and pressure after 5 hours with MCV wall thickness

MCV wall thickness (cm)	5	6	7	8	9	10
MCV peak pressure (MPa)	8.0	7.71	7.42	6.87	6.57	6.24
MCV pressure at 5 hour (MPa)	0.21	0.35	0.44	0.54	0.67	0.82

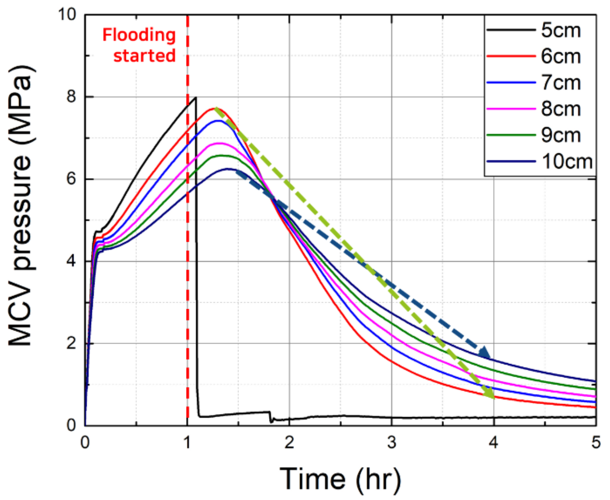

Fig 4. MCV pressure with MCV wall thickness

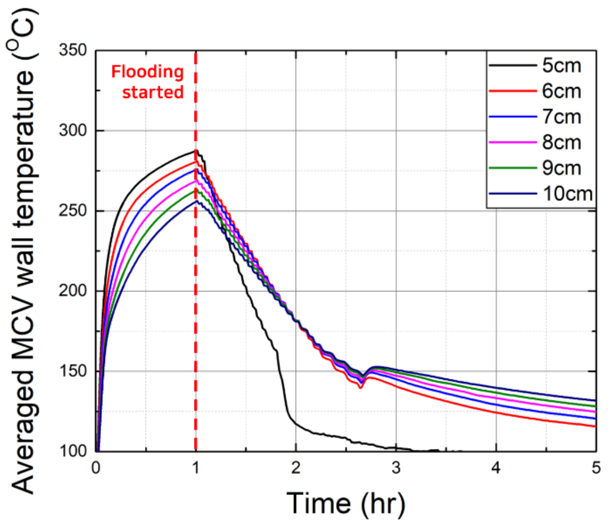

Fig 5. Averaged MCV wall heat structure temperature with MCV wall thickness

However, the trend in the MCV pressure changed as the time passed. Except for the 5 cm case whose MCV was damaged, the thicker MCV wall showed higher MCV pressure and temperature in about 2 hours. This change can be attributed to conduction, one of the major heat transfer mechanisms from the inside of the MCV to the cavity pool. The thicker MCV walls exhibited more heat transfer resistance. As shown in Fig. 6, the thinner MCV wall cases showed higher heat transfer to the cavity, indicating better heat removal performance. Therefore, the thicker MCV wall cases showed relatively lower coolability until the end of the calculation.

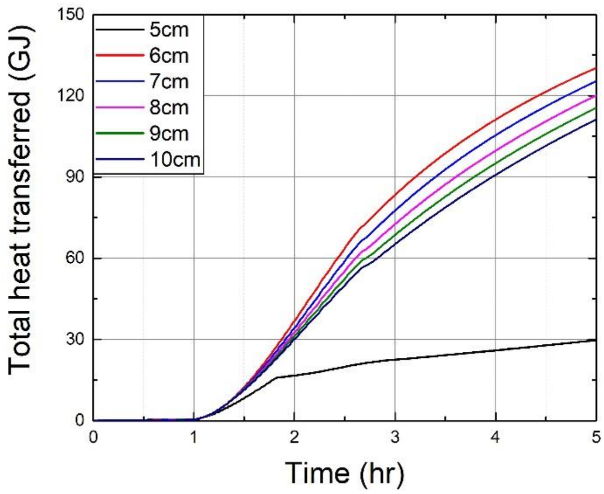

Fig 6. Total transferred heat from the MCV wall to the cavity

4. Conclusion

In this study, we conducted a sensitivity analysis of the MCV wall thickness effect on the coolability of the RM when using FSS. A 330 MWt NC-SMR was selected as the reference reactor, and numerical analyses using the MELCOR code were conducted for the postulated accident simulation. Major results, discussions, and conclusions can be summarized as follows:

- ✓ As the flooding of the cavity was initiated after the accident and reactor trip, the MCV wall structure acted as an initial temporary heat sink for the heat from the primary system.
- ✓ A thicker MCV wall provided higher heat capacity to withstand the heat but exhibited lower heat conduction performance.
- ✓ In the 5 cm case, the MCV pressure exceeded the design pressure, resulting in the MCV damage.
- ✓ For the MCV wall thickness ranging from 6 cm to 10 cm, the thicker MCV wall cases exhibited lower MCV peak pressure and wall temperature.
- ✓ However, this trend reversed after about 2 hours, with the thicker MCV wall cases showing higher MCV pressure and temperature.

From the results of this study, we could figure out the effect of the MCV wall structure thickness to the reactor integrity. Designing the MCV with greater thickness can indeed be advantageous in terms of the initial RM integrity. Furthermore, a thicker MCV wall structure may offer higher mechanical strength, which is crucial for securing the design pressure of the MCV. However, it's important to note that increasing the MCV wall thickness can potentially compromise the heat removal performance to the cavity. Cost, productivity, and mobility of the SMR also need to be considered carefully.

Acknowledgments

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