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Transient Analyses to Develop Event Trees of Autonomous Micro Modular Reactor

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1. Introduction

In order to make nuclear power plants (NPPs) safer and more economical, many advanced reactors are under development in many countries around the world. Several reactors have some common features such as small size, modular design, and passive safety systems. Autonomous micro modular reactor (MMR), which conceptual design is currently modified in Korea, also has these design features [1]. MMR is a direct supercritical CO2 (S-CO2) cooled modularized fast reactor which is designed to supply power to small villages in an isolated inland area. There are many advanced features to achieve such a goal. It adopts active and passive air-cooled decay heat removal system and autonomous load following operation feature.

As MMR is in its conceptual development stage, preliminary probabilistic safety assessment (PSA) may give insights for design improvements. As the first step of PSA, possible initiating events of MMR are identified by the review of other reactors with similar features. As representative cases among the initiating events, thermal-hydraulic analyses were performed for loss of coolant accident (LOCA), loss of load (LOL) event, and Loss of heat sink (LOHS) and preliminary event trees for the accidents were developed. After development of the event trees and fault trees for all the initiating events of MMR, it is expected that core damage frequency can be estimated and design improvements can be identified.

2. Safety Systems of MMR

Since MMR is a small-sized modular reactor, the safety system is relatively simple compared to typical pressurized water reactors (PWRs). In addition, there is no steam generator, because it is direct S-CO2 cooled fast reactor. In normal operation, the air fan removes the heat from the primary system through the precooler on the intermediate loop. Since the air fan and the CO2 circulator on the intermediate loop requires continuous electric power, they are not considered in mitigation strategies of accidents.

When there is no continuous electric power, four main safety features can be considered: feed valve, turbine bypass valve, venting valve and passive decay heat removal (PDHR) system. Firstly, turbine bypass valve makes bypass flow when the turbine rotational speed exceeds 110% of nominal value. This setpoint was set to reduces the turbine rotational speed under the safety limit 120%, to ensure the turbine integrity [2].

Venting valve is located at the turbine inlet and operates when the system pressure exceeds about 21MPa to prevent the overpressure. The setpoint is set to keep the system pressure lower than the limit of 24MPa.

Feed valve operates to replenish the inventory in the primary system when its pressure decreases below the containment pressure, such as LOCA. In LOCA, with the feed valve opening, the flow at the leakage flow and the flow at the feed valve is maintained, which makes the circulating flow between the system and the containment. There is no way to recover the system inventory immediately without the feed valve, because the rupture was assumed to occur at the compressor outlet.

PDHR system is devised to remove decay heat for long-term recovery after reactor trip. It passively cools down the system in the accidents instead of the air fan which needs power supply. Besides, the whole system is contained in two containments: inner and outer containment which is pressurized at 5MPa and 1MPa respectively. In this paper, the autonomous function is not considered in the accident mitigation, since it only works in normal operation.

3. Selection of Initiating Events for MMR

The design of MMR is quite different from the typical light water reactor (LWR), which means that initiating event lists must be reviewed. MMR is designed as a compact module including the turbomachinery so that it used S-CO2 as a coolant. It also does not have any steam generator and the coolant cool downs the core directly. Therefore, several reactor types can be considered in the selection of initiating evets such as PWR, boiling water reactor (BWR), gas-cooled fast reactor (GFR), and so on. Three event lists were reviewed, such as initiating event list of PWR in safety analysis report (SAR), transient event list of BWR developed by EPRI and presented by IAEA, and several accidents suggested to be analyzed in S-CO2 GFR [3,4].

Through this process, several initiating events were identified which have possibility to occur in MMR, such as LOCA, reactor vessel rupture (RVR), loss of load (LOL), loss of heat sink (LOHS), anticipated transient without scram (ATWS), and rod withdrawal or insertion as shown in the Table 1. For each initiating event, the accident scenarios were analyzed with Gamma+ code and the event trees were developed considering the success and failure of the safety functions.

Therefore, a number of analyses are necessary, and the operation of the passive systems would play an important role in risk assessment. In this paper, LOCA and LOL scenarios were analysed and the preliminary event trees were developed.

Table I: Initiating event list of MMR

Initiating event list of MMR	
Loss of coolant accident	Reactor vessel rupture
Loss of load	Loss of heat sink
Anticipated transient without scram	Rod withdrawal/insertion

4. Transient Analyses of MMR

4.1 Transient Analysis for LOCA

In this analysis, the analysis was performed with GAMMA+ code, which was originally developed by Korea Atomic Energy Research Institute (KAERI) and modified with S-CO2 data by MMR research team. In this paper, LOCA was analyzed with the variation of the break size: 0.064516m2 and 0.00064516m2 for large and small break LOCA (LBLOCA, SBLOCA), which are scaled sizes from LOCA in PWRs.

As shown in the Fig. 1, the pressure of the primary system started to decrease after the occurrence of LOCA. In the normal case, the reactor trip signal and the PDHR system actuation signal is generated at about 16MPa, and then negative reactivity is inserted, and the grid is disconnected from the generator in a second. When the pressure of the primary system decreased below the containment pressure, the CO2 in the containment passively injected to the primary system through the feed valve. For long-term cooling, PDHR system removes the decay heat from the core to the ambient air. Therefore, there are three safety features in normal LOCA scenario: reactor trip, feed valve opening, and PDHR system.

One of the safety features, reactor trip was simulated in the case of success and failure in LBLOCA and SBLOCA. The reactor trip failure case can be called LOCA without scram (LBLOCAWS). In LBLOCAWS, the cladding temperature increased up to 1084℃, which is still under the safety limit 1200℃. In all cases including SBLOCAWS, the peak cladding temperature (PCT), fuel centerline temperature, and the primary system maximum pressure did not exceed the safety limits. However, ATWS should remain in the initiating event list, because it must be verified that the results are the same for other initiating events.

The feed valve is located at the compressor inlet with the lowest pressure in the primary system. Without the feed valve opening, the code simulation was interrupted after the surge occurred. Surge mean that id the flow rated at the compressor decreases to a certain level or below, the flow rate becomes unstable and vibration occurs. The impact of this phenomenon on the core integrity should be ascertained through further analysis.

However, there is no way to recover the primary system inventory immediately without the feed valve in LOCA, it is assumed that the core might be damaged without the feed valve opening conservatively.

There are two PDHR trains capable of taking charge of 100% of heat removal in MMR for redundancy. One and two trains were assumed to fail to operate in LBLOCA and SBLOCA scenarios. As a result, the cladding temperature maintained the value below the safety limit when one train is assumed to fail to operate. Without the two trains, it was confirmed that the PCT exceeded the safety limit as shown in the Fig. 2. Thus, the success criterion for the PFHR system is determined to be one of the two trains working properly.

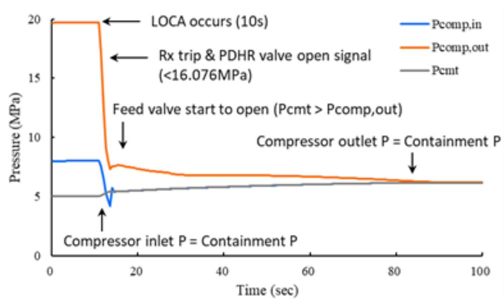

Fig. 1. Pressure of the primary system and the containment and the operating safety features in the normal LOCA scenario.

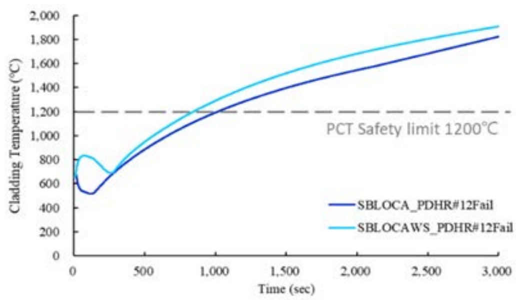

Fig. 2. Cladding temperature in SBLOCA scenario with two PDHR trains unavailable.

4.2 Transient Analysis for LOL

LOL is another important case to analyze for MMR. It can happen more often because the power grid on the construction site might be unstable. Unlike the LOCA situations, the pressure of the system in LOL scenario increased after the accident. Then the system pressure rapidly decreased after the reactor trip and the venting valve opening. When the system pressure reached 16.392MPa, the PDHR valve is opened and the turbine bypass valve is opened to remove for long-term cooling. Turbine bypass valve is opened when the turbine rotational speed is over 110% of nominal speed. Finally, the feed valve is opened when the pressure at the compressor outlet is lower the containment pressure. The pressure variation is shown in the Fig. 3. There are five safety functions operate in the LOL scenario:

reactor trip, venting vale, PDHR system, turbine bypass valve, and feed valve. These five functions are assumed to fail to develop an event tree.

In PWR, the control rods would be dropped passively if the power supply is cut off. However, there is not yet specified power source of the control system in MMR core, so that the reactor trip is considered in the LOL scenario. Even in the reactor trip failure case, the reactor power decreased after the few seconds due to the reactivity feedback effect. However, one of the important properties, the coolant temperature could not be maintained under the safety limit as shown in the Fig. 4. The safety limit 676℃ for the coolant temperature was set considering the integrity of the structure material such as pipes. Therefore, LOL without the reactor trip failure should be analyzed as ATWS.

When it comes to failure of venting valve opening, the pressure shows relatively high value without the venting valve opening, however it is still under the safety limit. The cladding temperature also showed low value under the safety limit. All the design parameters including the cladding and coolant temperature did not exceed the safety limits. However, in case of the LOLWS without the venting valve opening, the system pressure and the coolant temperature showed higher value above the safety limits 24MPa and 676℃ respectively. It does not mean the core damage in this case, the further analysis should be performed after exceeding the safety limit instead.

The turbine bypass valve is set to open when the turbine rotational speed exceeds 110% of nominal value. Without the bypass valve, the turbine rotational speed exceeded the safety limit, which is 120% of nominal value. The safety limit of the turbine rotational speed was determined from the turbine tip speed and some conservative assumptions in the previous study [2]. Conservatively, it is assumed that the turbine could be affected after the safety limit. The peak rotational speed is slightly higher than the safety limit and it might be seen too conservative assumption. Therefore, the impact on the core integrity need to be examined in the further study.

The feed valve works an important role in LOCA case. It feeds the CO_2 in the inner containment to the system to make up the inventory loss and makes the circulating flow between the system and the containment. However, in the LOL case, the results showed that the feed valve is not necessary. Even if the feed valve was not opened, the system pressure is similar to the containment pressure. The results showed that there is another pathway between the system and the containment. It means that the fluid flows back and forth through the venting valve instead of the feed valve as shown in the Fig. 5. Of course, the velocity of the flow is relatively low and the flow showed almost zero after a few seconds. The further study might show the venting valve opening instead of the feed valve can keep the plant status safe in LOL scenario. All the design parameters including the cladding temperature did not exceed the safety limits in the LOL scenario without the feed valve opening.

The PDHR train has an important role in long term residual heat removal in MMR. The PDHR system is connected between the core and the ambient air with two heat exchangers. There are two trains for redundancy. In the case of PDHR train #1 failure, there was not much difference from the normal operation. The other normal operating train replaced the part of the role of PDHR train #1. However, if both PDHR trains failed to operate, the cladding temperature exceeded the safety limit. As a result, the success criterion is determined to one of the two trains working properly.

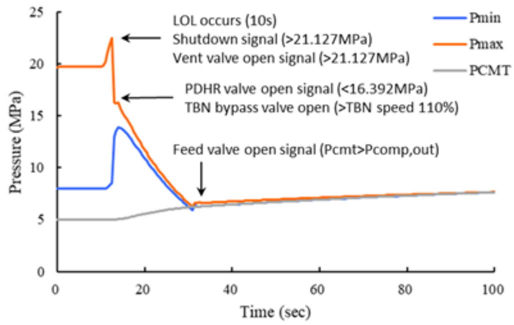

Fig. 3. Pressure of the primary system and the containment in the LOL scenario.

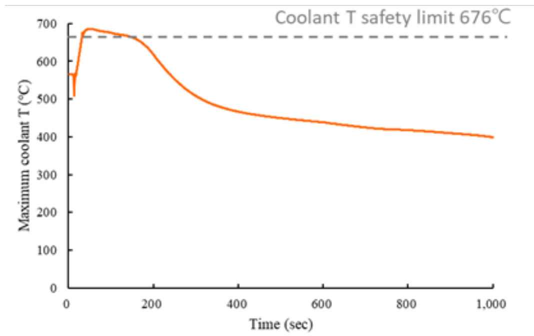

Fig. 4. Maximum coolant temperature in the LOL scenario without the reactor trip.

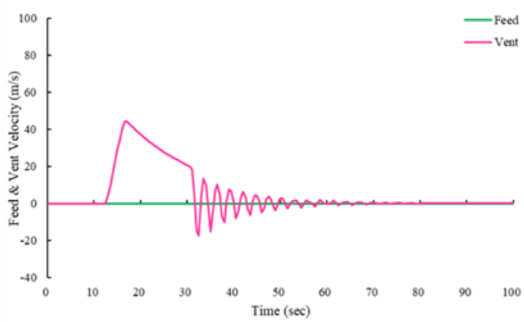

Fig. 5. Feed and vent velocity in the LOL scenario without the feed valve opening.

4.3 Transient Analysis for LOHS

Even if the offsite power is available, there is a possibility that the air fan will not work properly. Due to its own fault, the mass flow rate might not be enough to remove the heat. Therefore, the grid disconnection makes the only difference between LOL and LOHS scenario. After a result of thermal hydraulic analysis, the surge occurred a few seconds after the accident. It means that there is no evidence to prove the integrity of the core and the system is uncertain currently.

5. Development of Preliminary Event Trees for MMR

In this paper, we reviewed the results of the thermal hydraulic analysis for developing event trees for MMR in LOCA and LOL scenario. In LOCA scenario, the results showed that both feed valve and one PDHR train are required in both LBLOCA and SBLOCA. Although the results showed that the core would not be damaged, a more detailed analysis of UET and others is likely to be required. Without the feed valve opening, it is assumed that the core might be damaged conservatively. As a result, the preliminary event tree for LOCA were drawn as shown in the Fig. 6.

In addition to each failure of the safety functions mentioned above, dozens of analyses were performed taking into account each combination of safety functions. As a result of the LOL scenario, the preliminary event tree is developed as shown in the Fig. 7. In the current status, it is conservatively assumed that the core might be damaged if the safety limit is exceeded. An analysis of cases where each safety limit is exceeded will be carried out in the further studies.

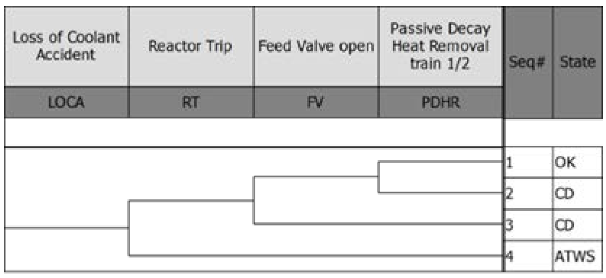

Fig. 6. Preliminary event tree for LOCA.

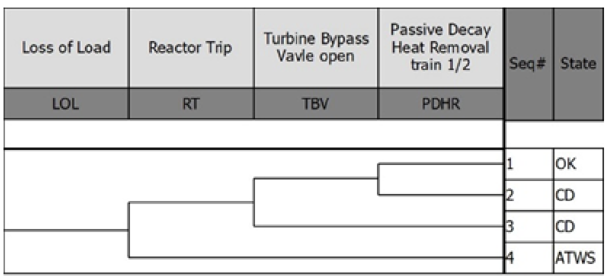

Fig. 7. Preliminary event tree for LOL.

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