Analysis of Beyond Design Basis Accident of S-CO_2 cooled KAIST Micro Modular Reactor with GAMMA+ code

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1. Introduction

Recently, a Small Modular Reactor (SMR) is receiving attention because of its flexibility and suitability for remote region where well developed electricity grid infrastructures cannot be found [1]. However, more innovations can further improve the economy and suitability of SMRs operating under such environment. Since most of the existing SMRs are designed to modularize reactor system and power conversion system (PCS) separately, still substantial construction work is required. This is because SMRs typically adopt a steam Rankine cycle, which commonly occupies large volume due to large components such as turbine and condenser as well as a water treatment system. To overcome this limitation of current SMR designs, Korea Advanced Institute of Science and Technology (KAIST) research team has developed a concept of fully modularized nuclear reactor with supercritical CO_2 (S-CO_2) as a coolant as well as the power conversion system fluid, namely KAIST Micro Modular Reactor (MMR) [2]. The most important aspects of MMR are compactness and an integrated system of nuclear reactor, PCS, safety system and containment altogether because MMR should be designed to be transportable with ship or truck. Based on these concepts, KAIST research team has optimized design of the system and analyzed system integrity under design basis accidents (DBA) such as loss of coolant accident (LOCA) and loss of load (LOL) [3]. For more conservative assessment of MMR, anticipated transient without scram with assuming single failure of a safety features (ATWS-SF) which is categorized beyond design basis accident (BDBA) will be assessed in this paper.

2. Methods and Results

2.1 MMR components

One of the highest priorities for designing a MMR is transportability, thus compactness and modularization are important factors while designing. Therefore, simple recuperated cycle is selected as the power cycle of MMR because this layout is the most compact and simple despite of marginally lower cycle efficiency than other cycle layouts. Heat exchanger and turbomachinery of MMR are used as printed circuit heat exchanger (PCHE) and radial type turbomachinery due to similar design requirement. Also, MMR is designed to be independent on water resource because MMR can be operating in the dry area like desert [2].

For compact reactor core, a drum-type control element is employed to reduce the core height by removing the axial movement of the conventional rod-type control system. Reactor core is designed to have a strong feedback coefficient, so the reactor power is autonomously controlled [4].

MMR is designed to operate in the remote area with a limited number of operators, so safety features of MMR should utilize passive mechanism to remove its decay heat when an accident occurs. In case of MMR, a passive decay heat removal system (PDHR) removes decay heat to ambient air with natural circulation. The driving force of the natural circulation is from the density difference and thermal center height difference between the core and the PDHR system and MMR has two PDHR systems for redundant safety features [2].

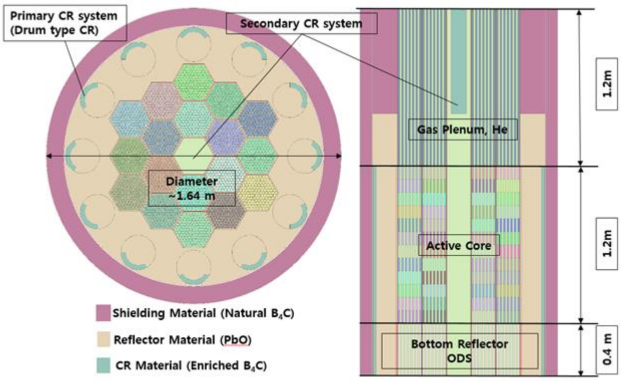

Fig. 1. Core layout of MMR

Table 1. Temperature coefficient of fuel material

Fuel Temperature Coefficient	-0.366 pcm/K
Coolant Density Coefficient	2.063 pcm/(kg/m^3)
Rod worth of primary control rod	3202.3 pcm
Rod worth of secondary control rod	1870.7 pcm

Table 2. Specification of Containment

Location	Dimensions	Volume	Weight
Containment (Outside)	6.8m (L) 4.0m (Dia.) 2.1cm (T)	1.69m^3	13.4 tons
Containment	5.5m (L)	3.49m^3	27.9 tons

(Inside)	3.2m (Dia.) 6.33cm (T)		

2.3 Set points of safety features.

To protect the system from postulated accidents, timely actions should be applied to MMR but the set points of the safety system under an event or accident are not fully optimized yet because a S-CO_2 closed Brayton cycle power plant is still under development. Therefore, based on the previous works for S-CO_2 cooled power cycle and by referring to the recommendation from ASME code [5] as well as the design criteria for similarly high pressure nuclear systems, the set points of MMR are determined. Table III summarizes each set point of safety actions.

Table III: Set points of safety features

Reactor trip set point (MPa)		Total delay time of reactor trip (ms)
Low Pressure	16.08	1150
High Pressure	21.13	1150
Safety action	**Set point**	
Valve opening rate	0.25/sec	
Turbine bypass valve opening signal	110% of nominal turbine rotational speed	
PDHR system injection signal	16.08 MPa	
Venting valve opening signal	21.13 MPa	
Feed valve opening signal	$P_{containment} > P_{compressor\ inlet}$	

Fig. 2 represents safety features of MMR. Turbine bypass is used to mitigate turbine over-speed under LOL. Venting valve is designed to depressurize over-pressure of the system by dumping inventory into inner containment. Feed valve is used for making up leaked inventory of primary side by using containment CO_2 inventory which is 36.8°C and 5.0 MPa.

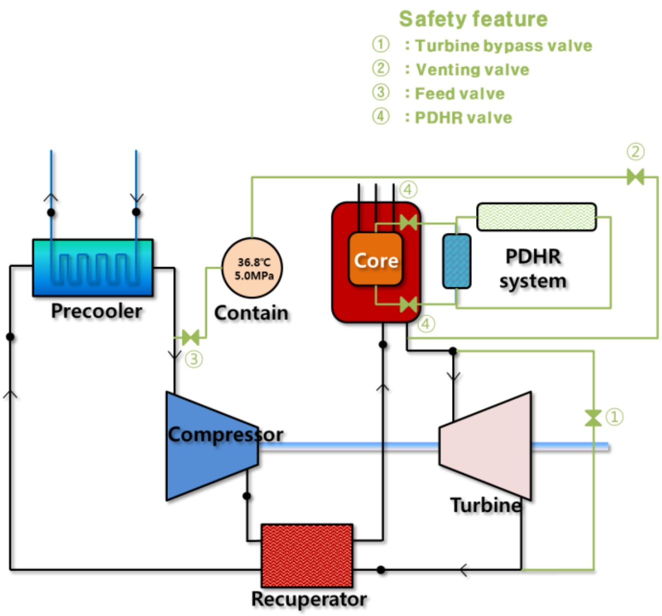

Fig. 2. Safety features of MMR

2.4 Results

Selected accident scenarios are loss of coolant accident without scram with assuming single failure of PDHR (LOCA-WS-SF) and loss of load without scram while assuming single failure of PDHR (LOL-WS-SF). Even though both ATWS-SF are categorized as very severe and unlikely accident scenarios (i.e. BDBA), MMR will be operated at remote region where a limited number of operators stays, so that MMR should be able to guarantee its integrity under any postulated accident scenario.

Since the place where MMR is operating can have an unstable grid infrastructure, loss of load is regarded as one of the important postulated accidents of MMR. The initiating event of LOL-WS-SF is abrupt separation of generator from the grid within 0.5 sec as shown in Fig. 3.

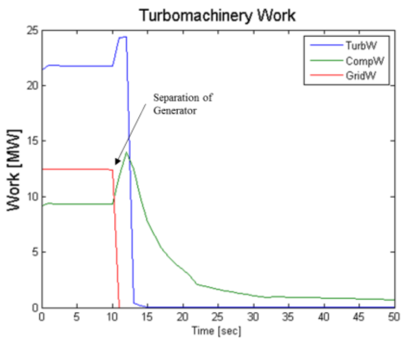

Fig. 3. Intiating event of LOL-WS-SF

Overall sequence of LOL-WS-SF is tabulated in Table IV. After separation of load, the turbine rotational speed is substantially increased. Since the compressor is connected to the turbine with shaft, increase of turbine rpm (i.e. increase of compressor rpm) leads to an increase of compressor pressure ratio, so the system pressure is initially increased at the beginning of the event. Therefore, high pressure shutdown signal and venting valve opening signal are generated. However, actuation of reactor scram is not implemented so that reactor core power is decreased only because of fuel temperature increase without external negative reactivity insertion (i.e. control rod) as shown in Fig. 4.

Table IV: Sequence of LOL-WS-SF

Time	**Event**	**Set Point**
10.0	Loss of load (0.5sec)	-
10.05	Loss of heat sink	Coincidence with separation of grid
11.62	Generation of high pressure shutdown signal	21.12 MPa
11.62	Generation of venting valve opening signal	21.12 MPa
13.07	Generation of PDHR valve opening signal	16.39 MPa
30.97	Generation of feed valve opening signal	$P_{containment} > P_{compressor\ inlet}$

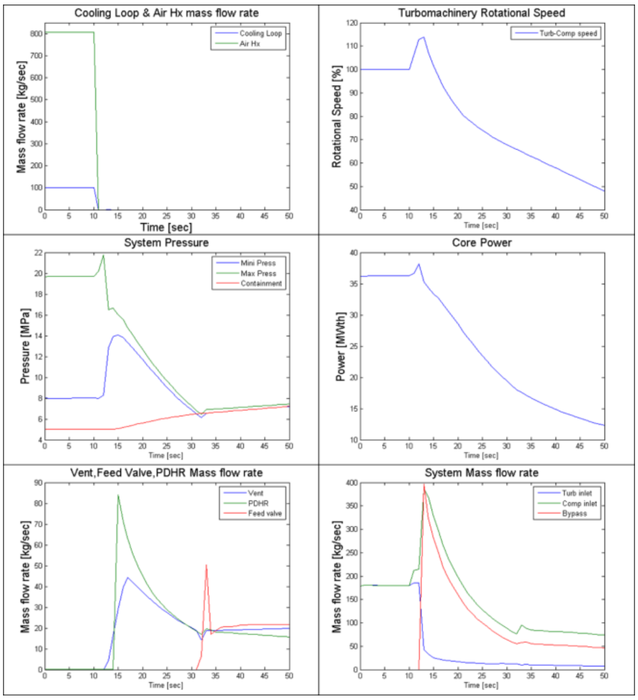

Fig. 4. Simulation results at the beginning of the LOL-WS-SF

When LOCA occurs to a nuclear system, it is hard to maintain cooling of the core because coolant is leaked from the primary system while leaving the nuclear reactor core under cooled due to coolant system depressurization. Especially, MMR is operating with highly pressurized CO_2 as a working fluid, so the consequence can be serious, once LOCA occurs. Since the compressor outlet has the highest density, rupture at this location leads to a large amount of leakage flow rate from the primary system. Thus, it can be concluded that MMR is determined to be safe under different types of LOCA if MMR maintains its integrity in LOCA at the compressor outlet. Generally, when break size is above $100in^2$, it is defined as large break LOCA. Thus, for conservative analysis, break size is determined as $100in^2$. The shutdown system is disabled and single failure of one of PDHR systems is assumed (LOCA-WS-SF). Fig. 6 shows initiating event of LOCA-WS-SF, which is a break of pipe at the compressor outlet and Table V summarizes the sequence of LOCA-WS-SF.

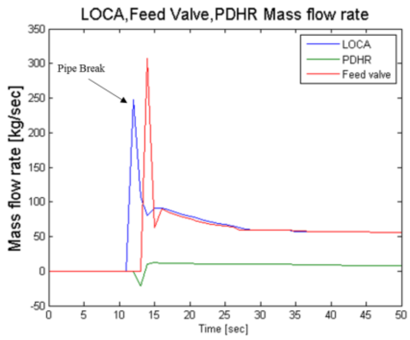

Fig. 6. Initiating event of LOCA-WS-S

Table V: Sequence of LOCA-WS-SF

Time	**Event**	**Set Point**
10.0	Pipe is broken with $100in^2$	-
11.61	Generation of low pressure shutdown signal	16.08 MPa
11.61	Generation of PDHR valve opening signal	16.08 MPa
12.55	Generation of feed valve opening signal	$P_{containment} > P_{compressor\ inlet}$

After pipe is broken at the compressor outlet, the pressure is dramatically decreased and safety measures such as feed and PDHR valve opening signal are activated due to low pressure signal based on Table III. After the feed valve operation, the compressor inlet mass flow rate is increased because the inventory in the containment flows into the compressor inlet pipe. Low pressure shutdown signal is generated but actual reactor trip is not activated. Separation of generator coincides with the reactor shutdown signal to protect grid. Since the system inventory is steadily reduced, turbine rotational speed is maintained below safety limit. Even though the reactor core is not shutdown, reactor power is reduced due to feedback effect of the reactor core as shown in Fig. 6.

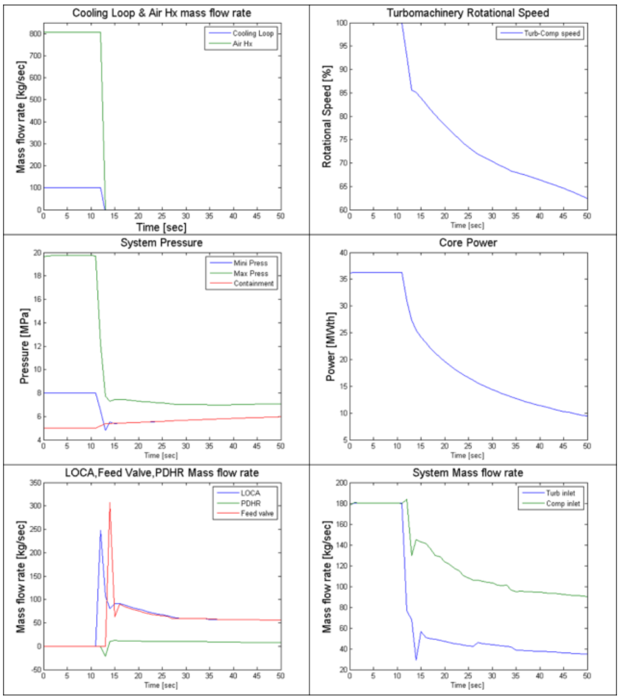

Fig. 6. Simulation results at the beginning of the LOCA-WS-SF

Additionally, safety limits of important safety parameters such as fuel and cladding temperatures, and pressure are determined based on ASME code and the safety limit of large water-cooled reactor. Table VI shows safety parameters of BDBA-SF compared to safety limits.

Table VI: Safety patameters of BDBA-SF

	T_{fuel} (°C)	T_{clad} (°C)	P_{max}(MPa)	Turbspd (%)
Safety limit	**2507.0**	**1200.0**	**24.0**	**125.0**
LOL-WS-SF	824.0	768.4	21.8	114.0
LOCA-WS-SF	1116.3	1097.4	20.0 (Nominal)	100.0 (Nominal)

3. Conclusions

The transient analyses results of beyond design basis accidents of the designed MMR are presented in this paper. This is to validate the designed safety system if those systems can protect MMR from the postulated accidents. Based on the previous works, the set points of safety features and safety limits are determined. The newly added safety features are safety valves such as feed valve, venting valve and turbine bypass valve to mitigate the accident consequences. A list of postulated accident scenarios for MMR are selected and modeled. The selected accident scenarios are: LOL-WS-SF and LOCA-WS-SF. For the selected accidents, severe fuel damage or melting is prevented, which demonstrates that MMR has capability to maintain its integrity under postulated accidents even when the core shutdown system failed.

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