Physics Investigation of a Supercritical CO2 cooled Micro-Modular Reactor (MMR) for Autonomous Load-Follow Operation

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Abstract. This paper presents a physics study for a passive autonomous load-follow operation in a supercritical CO_2-cooled micro-modular reactor (MMR). The proposed long-life 36.2 MWth MMR is a super-compact, fully-integrated, and truck-transportable fast reactor module in which all components are integrated in a single pressure vessel. UC fuel is considered to maximize the fuel inventory and to enhance neutron economy. The core lifetime is designed to be over 20 years without any refueling. To minimize the excess reactivity, a replaceable fixed absorber (RFA) is used and the resulting excess reactivity is found to be less than 1 $ during the whole lifetime of the core. For demonstration of a passive autonomous operation of the MMR, part load-follow operation are performed. In a passive autonomous part load-follow operation, the reactor power is automatically controlled by the feedback reactivity only, which mainly depends on the fuel and coolant temperatures. All neutronics calculations are performed using the continuous energy Monte-Carle Serpent code with the ENDF/B-VII.1 library and transient calculations are performed using modified GAMMA+ code.

Key Words: micro modular reactor, supercritical CO2 coolant, replaceable fixed absorber, long-life fast reactor.

1. Introduction

The micro-modular reactor is recently being developed as an alternative power source for remoted and isolated areas. [1]. It is a long-life small modular reactor that can be completely manufactured in a workshop and then easily transported to the designated site using the truck. Therefore, the MMR is designed to be a super-compact, fully integral nuclear power module where the reactor core, power conversion system, compressor, pre-cooler, recuperator, and safety systems are inside a single pressure module as depicted Fig. 1. The targeted design lifetime of the MMR is 20 EFPYs (Effective Full Power Years) about 51.6 GWd/MTHM. The reactor thermal power is 36.2 MWth and resulting total weight of the MMR module is just about 260 tons. This is possible because MMR has fast neutron spectrum and uses supercritical CO_2 (S-CO_2) as coolant.

The S-CO_2 coolant has a high power density so that the size of S-CO_2 Brayton cycle can be made much smaller than size of helium Brayton cycle and conventional steam Rankine cycle. In addition, the reactor can be directly coupled with the power conversion system without any intermediate heat exchanger. Also, the S-CO_2 Brayton cycle takes advantage of the higher thermal efficiency compared with the helium Brayton cycle (45% vs. 37% at the same turbine inlet temperature of 550 ℃) [2]. This motivated many researcher to investigate the S-CO_2 Brayton cycle for nuclear application. Direct cycle S-CO_2-cooled fast reactor concept for 200 [3] and 2400 MWth [4] have also been developed.

The preliminary MMR reactor design has been completed and characterized using a low enriched Uranium Nitride (UN), Uranium Carbide (UC) fuel and a replaceable fixed absorber

(RFA) [1,5]. Based on preliminary MMR design, UC fuel is chosen since UC fuel has a better compatibility with S-CO_2 coolant and has been extensively used in the gas-cooled reactor. Moreover, the core excess reactivity have been optimized using RFA concepts. It is preferable to have a maximum excess reactivity lower than 1.0 dollar during reactor operation to prevent the possibility of a prompt criticality accident. In this paper, resulting MMR core design is used for autonomous part load following operation

In addition, the transient core analyses are investigated with resulting MMR core design. GAMMA+ code [6], which is developed by KAERI for gas-cooled reactor system analysis, is modified for the S-CO_2 system analysis. However, GAMMA+ code should be modified to use S-CO_2 Brayton cycle. For the CO_2 properties, the NIST database [7] is used in the modified GAMMA+ code. With this modified GAMMA+ code, the load following characteristic of MMR is performed. Mass inventory controller, core bypass controller are used for adjusting demand of the load. Each automatic controller is designed by Ziegler-Nichols method and reactor power is autonomously controlled by the reactivity feedback coefficient.

This paper is organized as follows. Section 2 gives a description of the MMR concept and some of neutronics analyses of MMR. The autonomous part load follow simulations are described in Section 3. The conclusions are drawn in Section 4.

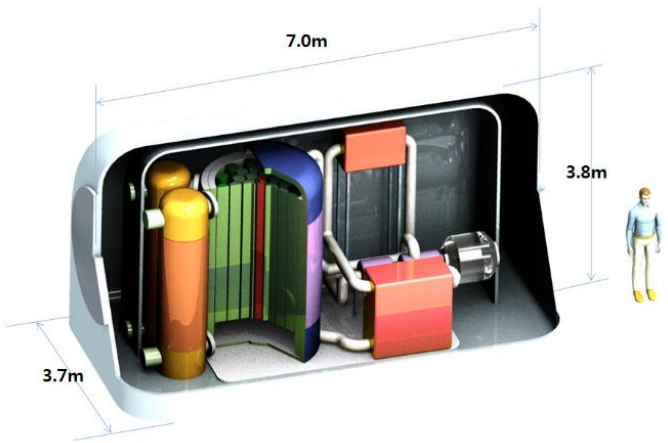
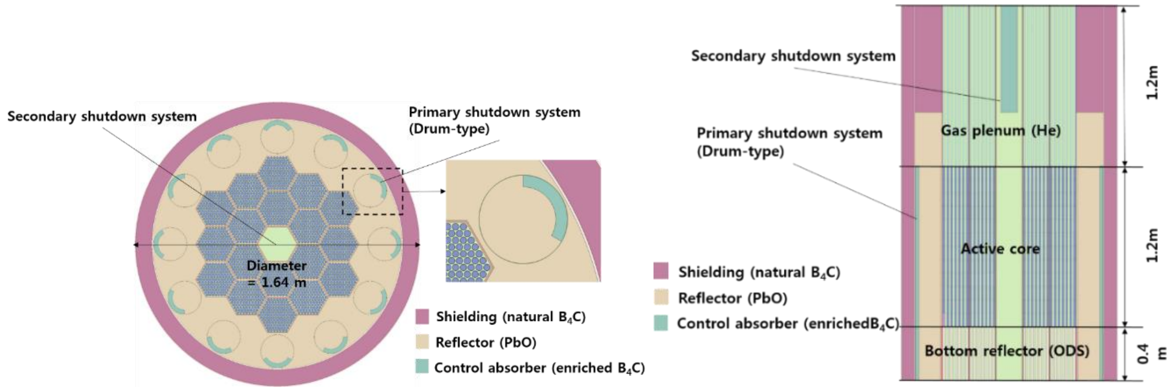


FIG. 1. Schematic layout of the MMR module

2. Design and Neutronics Analysis of Micro-Modular Reactor

Design configuration of the 36.2 MWth MMR is depicted in Fig. 2. The core consists of 18 fuel assemblies and they are surrounded by a thick PbO reflector housing 12 primary control drums and confined by a B_4C shielding layer in the outer region. One secondary shutdown system is located in the center of non-fuel region. The size of active and whole core are 1.2 m in height and 93.16 cm in diameter (active) and 2.8 m in height and 164 cm in diameter (whole). In the axial direction, a 40 cm-thick oxide dispersion-strengthened steel (ODS) axial reflector is located at the bottom of the core, while a 120 cm-thick gas plenum is located above the fuel region. During the normal operation, the reactor inlet and outlet coolant temperatures are 655 and 823 K, respectively, with the pressure of 20 MPa. The coolant speed is about 6.92 m/s. These design parameters of the MMR were determined through a system optimization study on the thermal performance [8]. The material compatibility was also accounted

A typical hexagonal ducted fuel assembly is used for MMR. There are 127 fuel pins in each fuel assembly which has same design parameters with design parameters of Ref. 1. For the reflector material, a lead-based material, PbO, is used to improve the neutron economy in the MMR core. The PbO reflector is contained inside an ODS canister and surrounds the core in a cylindrical shape with an equivalent thickness of 20 cm. Then, a 10 cm-thick natural enriched B_4C shield is located outside the reflector. The density of the B_4C shield is 98% of theoretical density. For the primary control drum and secondary control rod also have same design parameters with the ones of Ref. 1.



a. Radial core configuration *b. Axial core configuration*

FIG. 2. Radial and axial configurations of the MMR [1]

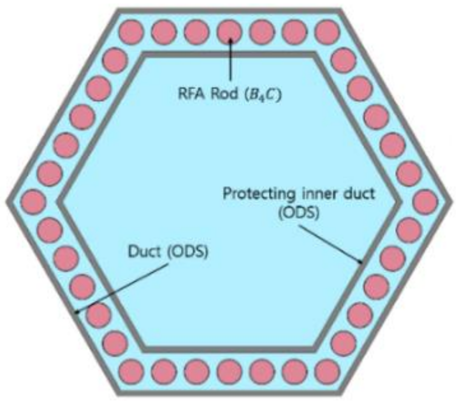


Fig. 3. Replaceable fixed absorber (RFA) concept

A ‘replaceable fixed absorber’ (RFA) [5] is used in to manage with the initial high core excess reactivity. The schematic concept of the RFA is depicted in Fig. 3. The RFA system is designed to have a high negative reactivity worth and it consist of several absorber rods. The required negative reactivity worth can be easily adjusted by removing some of its pins. In the BOC (beginning of cycle), several RFA rods are installed and whenever the core reaches a subcritical level, some of the RFA rods are removed from the core until the core reactivity is near 1$. Total 36 RFA rods with the same length as the fuel and 90% enriched B_4C with 70% TD are considered. The radius of RFA is 0.665 cm and each absorber rod is confined inside a 0.05 cm-thick ODS canister. A protecting inner duct is also installed to guarantee that the RFA rods will not block the movement of the secondary shutdown system.

Figure 4 shows optimized core excess reactivity in dollar for the 16.0% enriched UC-fueled core. The temperature for UC was assumed to be about 975 K. The cladding and coolant temperatures were assumed to be 866.4 K and 739.3 K, respectively. These temperatures were determined by a 1-D thermal-hydraulics analysis of the average channel in the MMR core. These analyses were performed with the assumption that heat is transferred radially from the outer surface of cladding to the bulk coolant via convection. The bulk coolant was determined by the coolant average temperature. Gnielinski’s correlation [9]

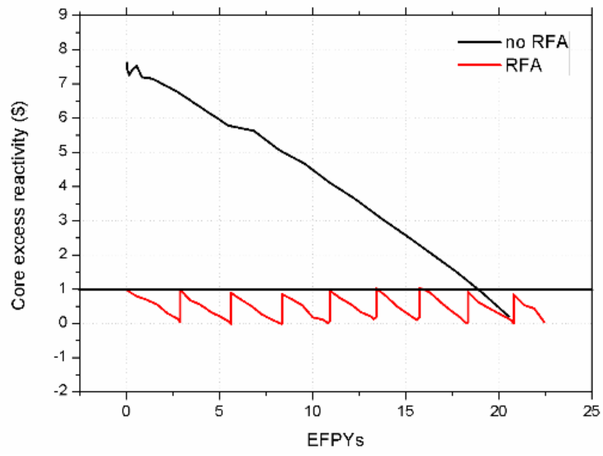


Fig. 4. Core excess reactivity, with and without RFA

The depletion results show that the maximum excess reactivity is minimized successfully to less than 1$ by adopting the rod-type RFA system. The total 9 cycles are required to maintain the core excess reactivity below 1$. In this analysis, the reactor is shut down for 50 days between each cycle for maintenance and removal of RFA. It is noted that the worth of a single RFA rod is not fixed. Instead, it depends on the core burnup and cycle. Initially, total 36 RFA rods suppress the excess reactivity and also the flux in the center core region. However, when some of the RFA rods are withdrawn, the flux in the center region increases. Consequently, the worth of the RFA rods will increases as the cycle goes on.

Because of the optimized core excess reactivity, ~1$, the natural enriched absorber is sufficient for the primary control system with 12 drums and 40% enriched absorber rod for the secondary shutdown control system is enough as listed in Table 2.

Table 2: Primary and secondary control systems worth

Control Worth	BOL (pcm)	EOL (pcm)
Primary drums		
Total	3,202.3 ± 28.8	2,791.5 ± 28.9
Total -1	2,889.1 ± 28.6	2,564.7 ± 27.9
Secondary	1,8707.7 ± 26.3	4,273.6 ± 29.6

As shown in Fig 5, the radial power is relatively flat at the BOL. At the EOL, the radial power becomes more center-shewed than at the BOL because of the complete removal of the RFA absorber.

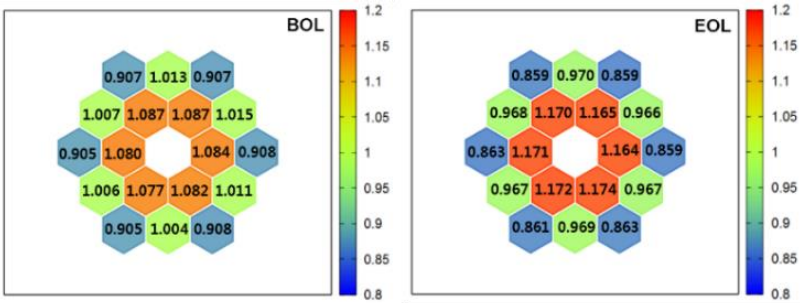


Fig. 5. Radial power distribution of UC-fueled core

Major reactivity coefficients such as fuel temperature coefficient (FTC), coolant temperature coefficient (CTC) and coolant void reactivity (CVR) are tabulated in Table 3. The FTC and CTC which are used in the autonomous load follow were evaluated with several temperatures and two temperature points, respectively. And CVR was calculated as the reactivity difference between normal and void condition. It is note that MMR have negative reactivity coefficients. The CVR at the BOL is negative and it becomes more negative at the EOL. This is due to higher axial neutron leakage through the central empty hole when the power profile becomes more center-skewed with the complete removal of the RFA pin. Table 4 tabulates the group-wise kinetic parameters which are used in the autonomous load follow.

Table 3: Major reactivity coefficients

Condition	**FTC, pcm/K**	**CTC, pcm/K**	**CVR, pcm**
BOL	-0.457 ± 0.02	-0.490 ± 0.17	-234.470 ± 16.8
EOL	-0.479 ± 0.03	-0.630± 0.18	-352.614 ± 17.0

Table 4: Group wise kinetic parameters of MMR

Energy group	**Beta value (β_i)**	**Lamda value (λ_i)**
1st group	2.163E-04 ± 0.0887	1.338E-02 ± 0.0005
2nd group	1.070E-03 ± 0.0406	3.242E-02 ± 0.0005
3rd group	1.053E-03 ± 0.0411	1.215E-01 ± 0.0003
4th group	2.835E-03 ± 0.0258	3.095E-01 ± 0.0007
5th group	1.350E-03 ± 0.0372	8.740E-01 ± 0.0010
6th group	5.739E-04 ± 0.0564	2.937E+00 ± 0.0014
Effective	7.099E-03 ± 0.0158	5.525E-01 ± 0.0218

3. Part Load Follow Operation

The MMR should be responding to the grid demand autonomously because it is designed to be able to operate in the remote area with limited number of operators. In conventional thermal reactor, the reactor power is adjusted by insertion of external reactivity such as control rod and borated water. By contrast, the power of fast reactor can be controlled by its reactivity feedback mechanism inherently. Similarly as fast reactor, the reactor power of MMR can be autonomously and quickly adjusted as the grid demand changes with time because of its strong reactivity feedback.

In this autonomous part load following operation, the power conversion system maintains turbine rotational speed (frequency of electricity) and high cycle efficiency (or high turbine inlet temperature) in priority. When the grid demand is changed, the decrease of core mass flow rate which leads to reduction of turbine work should be matched with the core.

Typically, there are three method for part load follow operation; (1) core bypass control method, (2) mass inventory method and (3) turbine throttling control method. These three methods lead to reduction of core mass flow rate but each method has different consequence and response time. (1) Core bypass control method is the most quickly responding control to maintain the turbine rotational speed at the nominal speed. When current rotational speed is higher than the nominal value, the core bypass valve is opened, so that the turbine mass flow rate is reduced to reduce the turbine rotational speed and core bypass valve is closed for the opposite case. (2) Mass inventory control method control the system mass to maintain the turbine rotational speed. It is known for achieving high cycle efficiency but the response is relatively slow. Therefore, it is difficult to maintain turbine rotation speed which has to be controlled with quick responsive controller if only mass inventory control is applied. Thus, the mass inventory controller has to be combined with the core bypass controller. (3) Turbine throttling control method uses forced pressure drop at the turbine inlet to match turbine work. If the turbine inlet pressure is decreased with the valve operation, the pressure ratio of turbine is also reduced, so that it finally leads to the reduction of turbine mass flow rate [10]. Figure 6 shows the location of each control valve.

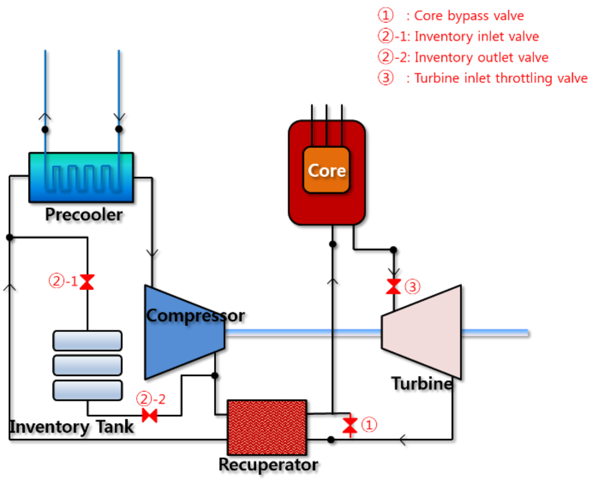


Fig. 6. Location of control valve in MMR module

Based on the cycle efficiency, the combination between core bypass control method and mass inventory method is chosen for the MMR module. When the grid demand changes, proper total mass of CO_2 should be determined for the corresponding grid demand. The optimal total mass of MMR for different grid demand is pre-calculated with the modified GAMMA+ code. Therefore, if the total mass for the current grid demand is smaller than the required total mass, the inventory inlet valve is opened and the inventory outlet valve is closed to insert CO_2. The opposite way is used in the opposite case. Table 5 tabulates the appropriated total mass for each grid demand and cycle efficiency of simulated part load follow operation. The PID parameters of mass inventory and core bypass control were determined by applying Ziegler-Nichols tuning method.

With this automatic core bypass and mass inventory controller, the part load follow operation of MMR is simulated with the modified GAMMA+ code. Figure 7 shows a linear step change (10%) of grid demand and turbomachinery's work.

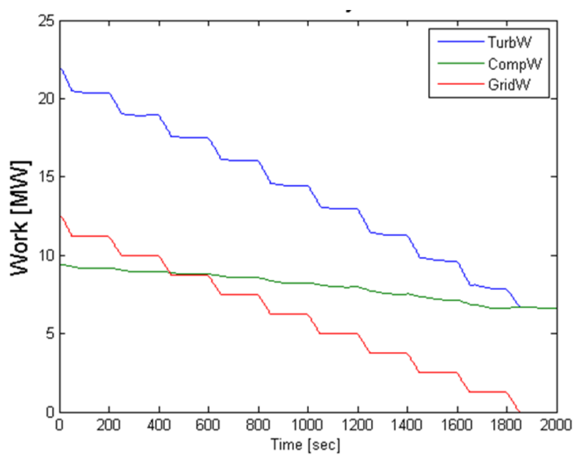


Fig. 7. Grid demand and turbomachinery work during part load follow operation.

Figure 8 shows the fraction of control valve both core bypass and inventory and turbine rational speed of simulated results during the part load follow operation. Figure 9 shows the system pressure and mass flow rate. When both inventory and core bypass control cope with the change of grid demand, the turbine work is controlled by adding or subtracting CO_2 inventory in the cycle. Therefore, the mass flow rate of turbine and compressor have similar trend and values. And Fig 10 shows the autonomously adjusted core power and reactivity.

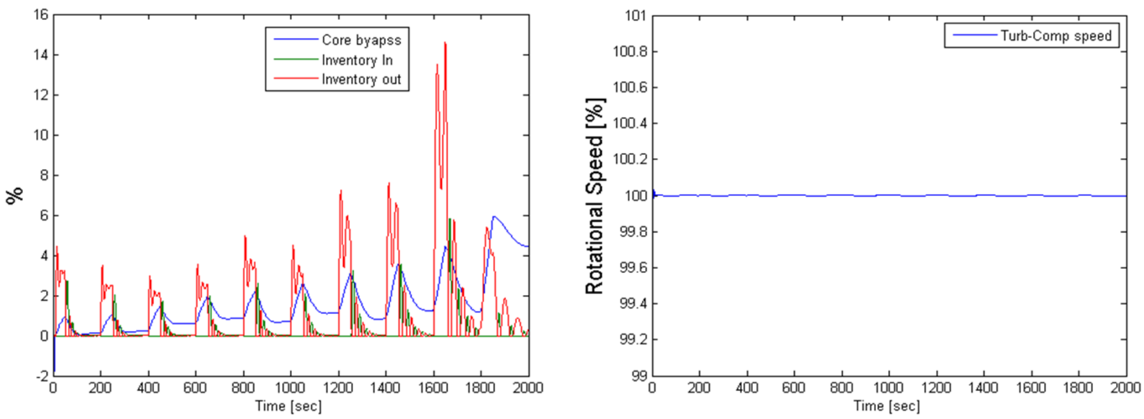


Fig. 8. Control valve fraction and turbine rational speed during part load follow operation

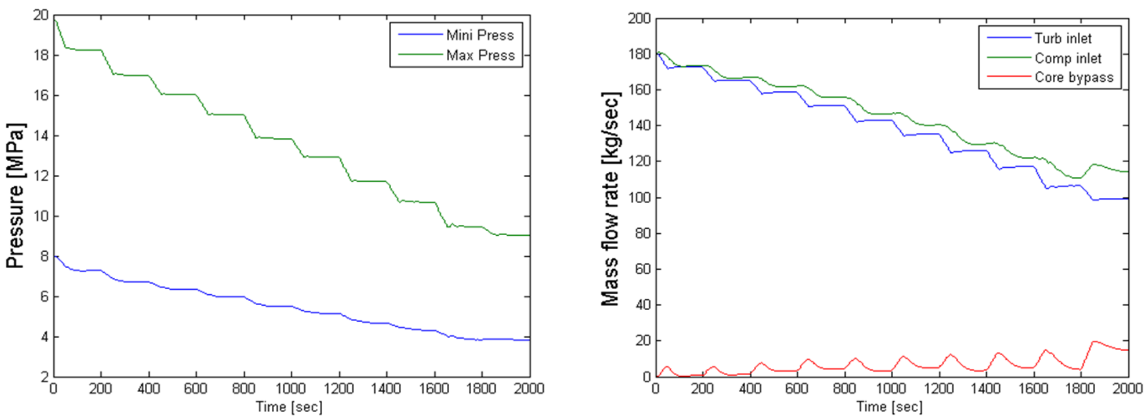


Fig. 9. System pressure and Mass flow rate during part load follow operation

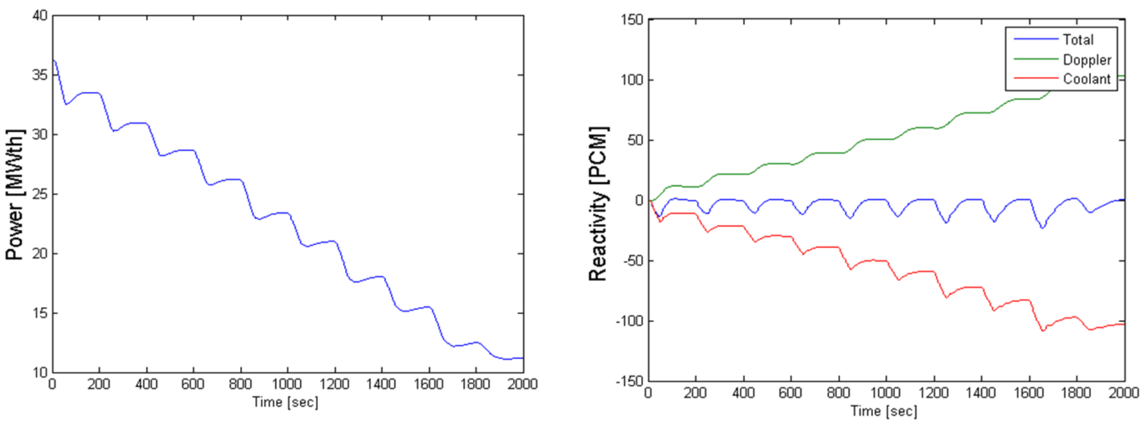


Fig. 10. Core power and Reactivity during part load follow operation

Table 5: Quasi-steady state results of mass inventory with modified GAMMA+ code

Load (%)	Grid Demand (W)	Total Mass (kg)	Reactor Power (W)	Cycle efficiency
100	12467481	6949.94	36180000	0.3445959
90	11220732.9	6913.95	33966900	0.3303432
80	9973984.8	6882.58	31996600	0.3117201
70	8727236.7	6858.54	29414600	0.2966974
60	7480488.6	6832.92	26455800	0.2827542
50	6233740.5	6801.41	24019900	0.259524
40	4986992.4	6777.36	21908700	0.2276261
30	3740244.3	6744.7	19222600	0.1945754
20	2493496.2	6718.74	16160000	0.1543005
10	1246748.1	6686.17	13832400	0.0901324
0	0	6679.17	11050100	0

4. Conclusions

In this paper, autonomous part load follow operation of MMR was performed. For steady-state design and kinetic parameters, the latest MMR design is used which is UC-fueled long-life MMR with direct S-CO_2 Brayton cycle. For the absorber design, thirty-six RFA rods are installed at the BOC, and they are meant to be removed from the reactor when the core reactivity becomes subcritical during the operational lifetime. The number of removed RFA rods is adjusted so that the core criticality is less than 1$. Based on this strategy, the core excess reactivity was successfully minimized.

From the steady state results of MMR, the part load follow operation is simulated. Since MMR is likely to be installed in the remote region a limited number of operators, MMR has to automatically adjust the system setting when there is a change in the grid demand. MMR adopts only two automatic controllers which are core bypass and inventory controllers because two controllers are enough to maintain cycle performance in terms of safety and efficiency during normal operation. Based on above preliminary part load follow results, the feasibility of load follow operation of MMR is demonstrated. In addition, we will implement full daily load follow operation.

5. Acknowledgements

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