Investigation on Transient Behaviors of the Truly-Optimized SMR ATOM

Yunseok Jeong[a], Taesuk Oh[a], and Yonghee Kim[a]*
[a] *Korea Advanced Institute of Science and Technology (KAIST)*
291 Daehak-ro, Yuseong-gu, Daejeon, Korea, 34141
**yongheekim@kaist.ac.kr*

1. Introduction

The water-cooled small modular reactors (SMRs), which incorporate advanced passive safety features and enhanced economic feasibility, are recognized as one of the next-generation reactors. Since such technology stems from the matured PWR design, the soluble boron (SB) is often included as a means of reactivity control, which also stifles the power distortion. However, its presence in the reactor core insinuates inflexible reactor power control and could hamper safety due to near-zero moderator temperature coefficient (MTC) at high concentration. In addition, the usage of soluble boron necessitates the complex chemical and volume control system (CVCS), which altogether impairs the economics of the SMRs.

In contrast, the exclusion of soluble boron, i.e., soluble-boron-free (SBF) reactor design, not only allows efficient usage of fuels but also reduces the overall cost of the reactor due to the neglection of CVCS. Furthermore, it was shown that the SBF design is more favorable in terms of passively autonomous load-following operation (PALFO) and frequency controls, which are cumbersome to be met for current third-generation nuclear power plants.

The inclusion of soluble boron dictates the reactor core to be under-moderated since it results in a positive temperature feedback. Hence, the SBF reactor could further exploit the fissile materials by strengthening the extent of moderation. Alongside the utilization of innovative centrally-shielded burnable absorber (CSBA) to control the reactivity swing during operation [1], optimization regarding the disposition of fuel rods and the moderator has been made for SBF SMR design named autonomous transportable on-demand reactor module (ATOM) [2]. Such original fuel lattice design is referred to as 'truly-optimized PWR' (TOP) which pursues optimal usage of fuel under SBF environment.

In this study, the transient behaviors of two-batch ATOM core based on TOP lattice design is investigated to check the feasibility of PALFO through sole adjustment of feedwater flowrate in the steam generator and reactor startup which only includes control rod movement. Note that startup operation of interest begins from hot zero power (HZP) to hot full power (HFP) where control element assembly (CEA) control logic named Mode-Y is implemented [3]. An in-house time-dependent nodal code with thermal-hydraulics (TH) analysis named KAIST Nuclear-reactor Simulator 3D (KNS3D) was used for both PALFO and the reactor startup simulations.

2. Neutronics and Thermal-Hydraulics Modeling

KNS3D is an integrated nodal code based on NEM-CMFD acceleration which supports TH-coupling, quasi-static transient, and steam generator coupling. In this study, both reactor startup using Mode-Y and PALFO are performed with a time-dependent manner. The flowchart of KNS3D in TH-coupled time-dependent calculation is shown in Figure 1, where capital Q is a vector including the fuel temperature and the coolant temperature of a certain node. Capital XS means the real cross section used in the nodal calculation, which considers control rods, temperature feedback, and poison. A detailed description of time-dependent TH module is explained in Figure 2. In the case of PALFO, an in-house helical coil steam generator (HCSG) solver was used to obtain the inlet coolant temperature whereas the programmed inlet coolant temperature was given in the reactor startup process.

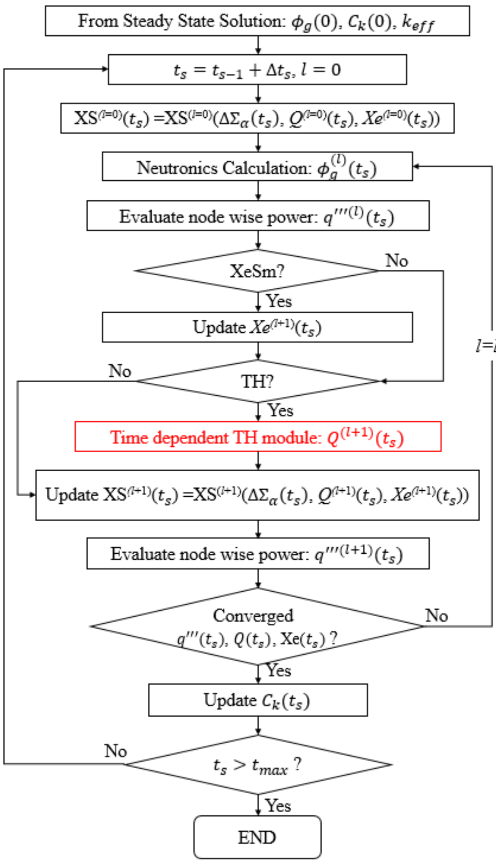

Figure 1. Calculation flowchart of KNS3D

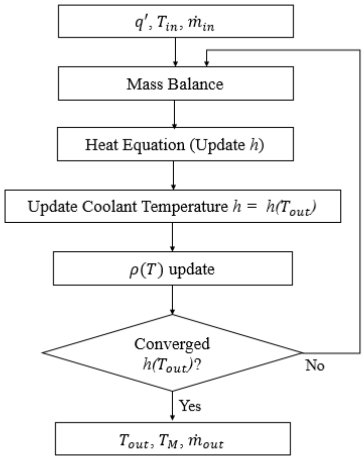

Figure 2. Time-dependent TH flowchart of KNS3D

3. CEA Control Logic Mode-Y

In the reactor startup simulation, the CEA control logic Mode-Y was utilized to autonomously control the CEAs according to the demand power. Figure 3 shows the CEA pattern of the ATOM core, Figure 4 illustrates the temperature dead-band alongside the movement speed of CEA, and Figure 5 describes a detailed control strategy of CEAs in the ATOM core which is referred to as Mode-Y. Since shutdown banks are withdrawn for HZP condition, they are neglected in the Mode-Y description for HZP startup.

Both withdrawal and insertion of CEAs are determined with 30% overlapping condition using the temperature difference between the measured coolant outlet temperature and the target coolant outlet temperature. Note that the movement speed also differs with respect to the magnitude of the temperature difference.

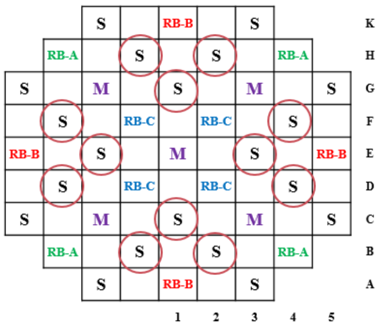

Figure 3. CEA pattern of the ATOM core

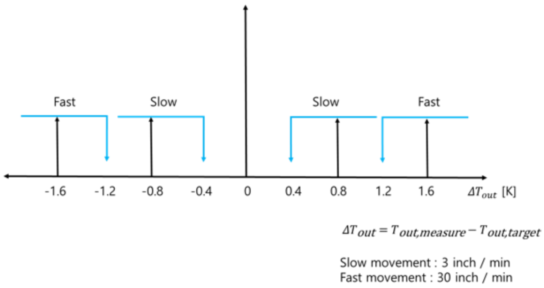

Figure 4. Dead-band of Mode-Y

Condition			Selected Group	Effect
	Direction	Rod Position		
$\|\Delta T\| <$ deadband	-	-	-	-
$\|\Delta T\|>$deadband $\Delta T < 0$	Withdrawal	**If** $H_{RB-C} < H_{Overlap}$	RB-C	Increase of outlet T
		Else if $H_{Overlap} < H_{RB-C} < H_{top}$	RB-B, RB-C (half step)	
		Else if $H_{RB-B} < H_{overlap}$	RB-B	
		Else if $H_{overlap} < H_{RB-B} < H_{top}$	RB-A, RB-B (half step)	
		Else if $H_{RB-A} < H_{top}$	RB-A	
		Else	MS	
$\|\Delta T\|>$deadband $\Delta T > 0$	Insertion	**If** $H_{MS} > H_{bottom}$	MS	Decrease of outlet T
		Else if $H_{bottom} < H_{RB-A} < H_{overlap}$	RB-A	
		Else if $H_{Overlap} < H_{RB-A} < H_{top}$	RB-A, RB-B (half step)	
		Else if $H_{bottom} < H_{RB-B} < H_{overlap}$	RB-B	
		Else if $H_{overlap} < H_{RB-B} < H_{top}$	RB-B, RB-C (half step)	
		Else if $H_{RB-C} < H_{top}$	RB-C	

Figure 5. CEA movement logic of Mode-Y

4. Numerical Results

4.1 Reactor Startup

In the reactor startup, the beginning of cycle (BOC) condition was adopted. The initial power is assumed to be 0.1% (0.45MWth) and Xe-135 number density is at equilibrium state while Sm-149 number density is set to zero due to its slow accumulation rate at low power. The demand power increases to 15% during the first 2 hours and it remains constant for another 3 hours to consider electricity grid connection. The demand power then further ascends to 100% during 10 hours. During the startup, CEAs are solely controlled by Mode-Y.

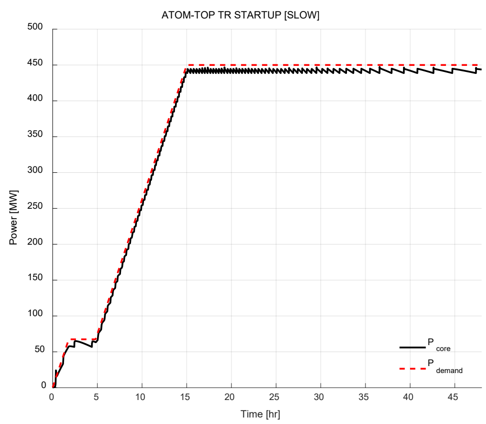

Figure 6. Core power vs. Demand power during startup

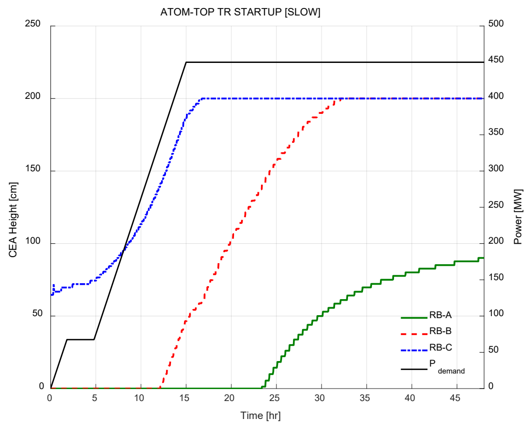

Figure 7. CEA position during startup

Figures 6 and 7 show the core power variation and corresponding CEA locations with demand power, respectively. It is clear that the core power follows the demand power within the temperature dead-band. In Figure 7, three CEAs are withdrawn with 30% overlapping to compensate for the negative reactivity originating from Xe-135, Sm-149, and temperature rise of the reactor when the coolant temperature is out of the dead band.

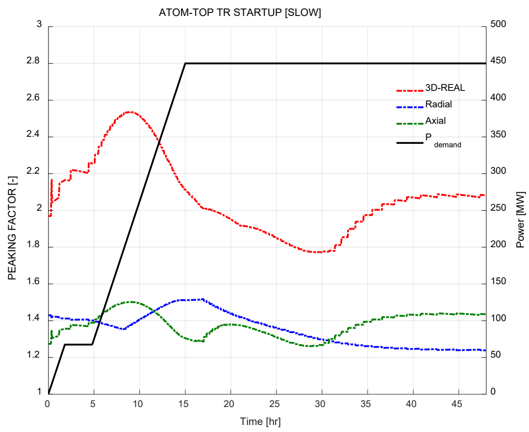

Figure 8. Power peaking profile during startup

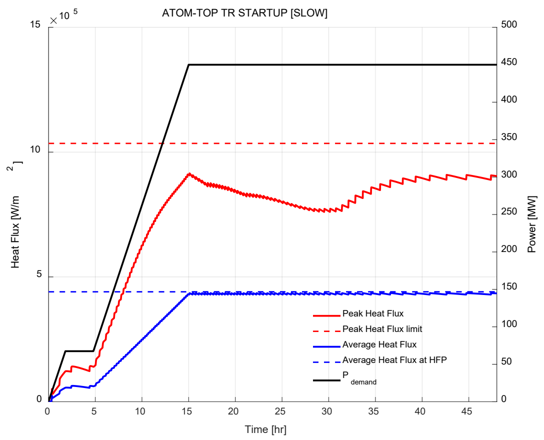

Figure 9. Heat flux profile during startup

The power peaking factor profile and the heat flux profile during startup are illustrated in Figures 8 and 9, respectively. It should be noticed that the values of 3D-peaking factor and the peak heat flux are obtained from the nodal calculation, and the local peaking factor of 1.1 is then additionally multiplied for each factor. Nevertheless, the 3D-peaking factor and the peak heat flux are acceptable while considering a maximal 3D peaking factor of 2.35 for HFP condition according to most of the nuclear design reports.

4.2 Passively Autonomous Load-Follow Operation

In PALFO, the beginning of the cycle (BOC) condition was postulated, where the simulation starts from the HFP equilibrium Xe-135 and Sm-149 state. The demand power descends to 50% during 3 hours and stays constant for 12 hours. Subsequently, the demand power increases to 100% during 3 hours and stay at 100% power for 24 hours. The feedwater flowrate of the steam generator is controlled by the demand power accordingly. This power ramp-down and up is repeated in the simulation, and the secondary frequency control which manipulates the core power up to ±5% is simultaneously performed during the PALFO. Such a scenario where the power remains at 50% for a long time was deliberately chosen to impose a stringent PALFO condition due to Xe-135 variation.

Figure 10 depicts the evolution of core power during PALFO simulation while incorporating a rapid secondary frequency control (spiky peaks in the cartoon). The estimated core power well resembles the demand power by solely controlling the feedwater flowrate of the steam generator. As illustrated in Figure 11, Xe-135 number density increases and decreases with the demand power, where the deviation between the maximal and the minimal number density is about 36% of the initial number density, which induces a significant reactivity swing in the core. However, as shown in Figures 12 and 13, the coolant temperature and the doppler fuel temperature feedback can accommodate such a large Xe-135 swing due to a sufficiently negative MTC value.

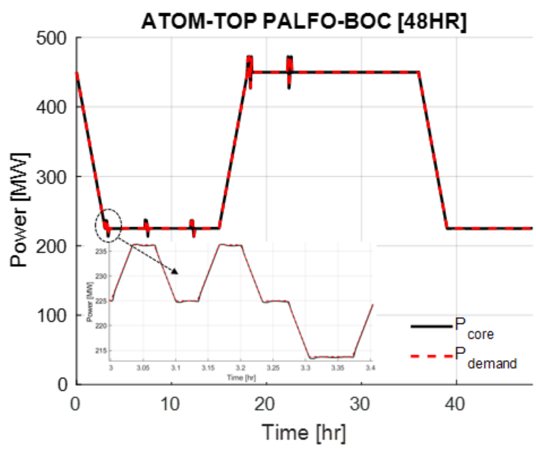

Figure 10. Core power vs. Demand power during PALFO

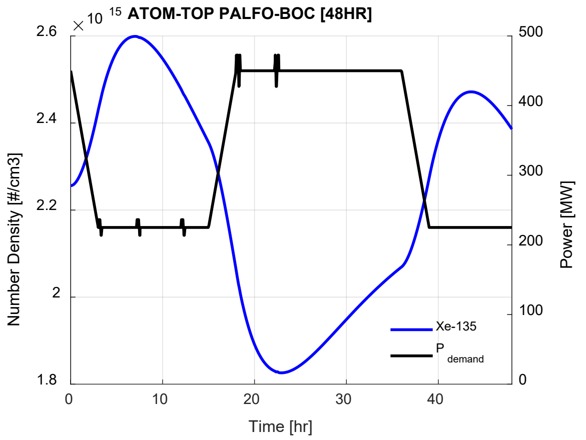

Figure 11. Xe-135 number density during PALFO

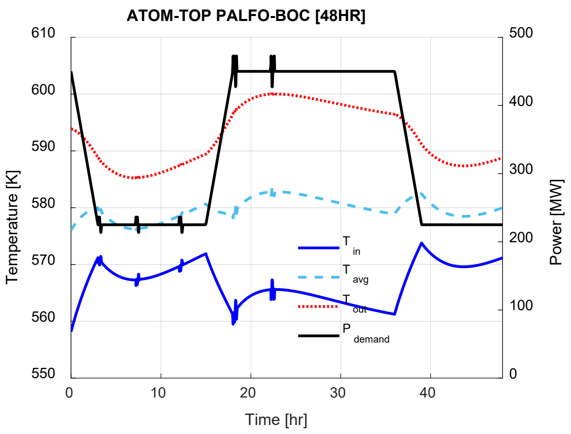

Figure 12. Coolant temperature profile during PALFO

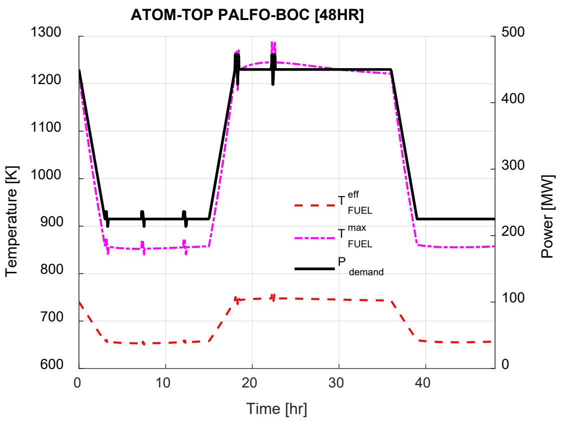

Figure 13. Doppler fuel temperature profile during PALFO

5. Summary and Conclusions

In this study, the hot zero power reactor startup using control rods and passively autonomous load-follow operation of optimized ATOM core are investigated with an in-house nodal code KNS3D. During the startup, CEAs are controlled by the control logic "Mode-Y" with 30% overlapping condition. It was found that the core power rises within the temperature dead-band, and both power peaking and peak heat flux are sufficiently low, which implies the possibility of the autonomous startup in SBF condition. The passively autonomous load-follow operation which has a large Xe-135 variation was also investigated. The results clearly exhibit that it is feasible to realize such operation only through adjustment in the feedwater flowrate on the secondary side, which stems from the sufficiently negative MTC of the optimized ATOM core.

For further studies, the burnup-dependent transient results such as the middle of cycle and end of cycle will be contemplated. Moreover, the heat flux of fuel rods was simply evaluated using nodal power in this study. Therefore, pin-power reconstruction should be performed to determine the accurate peak pin power in the hottest fuel assembly for a more realistic evaluation.

ACKNOWLEDGEMENTS

This research was supported by the KAI-NEET, KAIST, Korea and the National Research Foundation of Korea (NRF) Grant funded by the Korean Government (MSIP) (NRF-2016R1A5A1013919).

REFERENCES

[1] Nguyen, Xuan Ha, ChiHyung Kim, and Yonghee Kim. "An advanced core design for a soluble-boron-free small modular reactor ATOM with centrally-shielded burnable absorber." *Nuclear Engineering and Technology* 51.2 (2019): 369-376.

[2] Nguyen Xuan Ha, Seongdong Jang, and Yonghee Kim. "Truly-optimized PWR lattice for innovative soluble-boron-free small modular reactor." *Scientific reports* 11.1 (2021): 1-15

[3] Yunseok Jeong, "A Study on Multiphysics Startup simulation of the Soluble-Boron-Free ATOM System", M.S. Thesis, KAIST, 2021