Load-Follow Performance of Soluble-Boron-Free ATOM Using the Mode-Y Logic

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1. Introduction

The water-cooled SMRs have been designed based on the use of soluble boron because it does not distort the power distribution. However, it can be clearly noticed that the use of soluble boron could hamper the safety of the reactor due to near-zero moderator temperature coefficient at high concentration and swift power maneuvering cannot be obtained with the boron control. Furthermore, it needs a complex chemical and volume control system which increases the cost of nuclear power plants. Meanwhile, according to the European Utilities Requirements, the modern nuclear power plant must at least be capable of daily load-follow operation with change of electric output of up to 3-5% of rated power per minute, which implies that the soluble-boron-free SMR is more desirable in terms of power maneuverability [1].

In order to circumvent those adversities of soluble-boron based SMRs, many soluble-boron-free SMRs have been proposed. However, most of them could not attain the competitiveness against commercial LWRs and other types of SMRs due to the lack of appropriate burnable absorber designs and the difficulty of cold shutdown margin criteria with the limited number of control element assemblies (CEA). Among them, an advanced soluble-boron-free core design named ATOM is chosen in this study since it has solved present issues about the cold shutdown margin and burnable absorber designs [2,3].

In this study, the load-follow operation performance of soluble-boron-free ATOM core is investigated with the CEA control logic Mode-Y. An in-house time-dependent thermal-hydraulics coupled nodal code named KAIST Advanced Nuclear Tachygraphy (KANT) was used for the simulations.

2. Neutronics/Thermal-Hydraulics Modeling and Reactor Characteristics

The in-house reactor nodal analysis code KANT is based on the NEM-CMFD (Nodal Expansion Method-Coarse Mesh Finite Difference) scheme which can be coupled with assembly-wise thermal-hydraulics analysis. It was postulated that there is no cross-flow between neighboring fuel assemblies, no axial conduction in the fuel and coolant, and the pressure drop in the coolant channel is neglected. The conventional two-step method was utilized for time-dependent numerical results and the burnup-dependent cross-sections, temperature coefficients, and assembly discontinuity factors are calculated by using Serpent-2 code with ENDF/B-VII.1 library. In the load-follow operations using CEAs, the steam generator is decoupled and programmed inlet coolant temperature is given with a constant average coolant temperature strategy.

The ATOM core is a soluble-boron-free reactor designed to generate 450MWth with an innovative burnable absorber called centrally-shielded burnable absorber. In Figure 1, the radial and axial layout of the ATOM core is illustrated and Figure 2 shows the CEA pattern of the ATOM core. The detailed description on the CEA is written in Table 1.

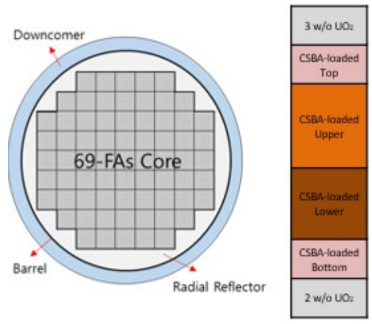


Figure 1. Radial and Axial Layout of ATOM

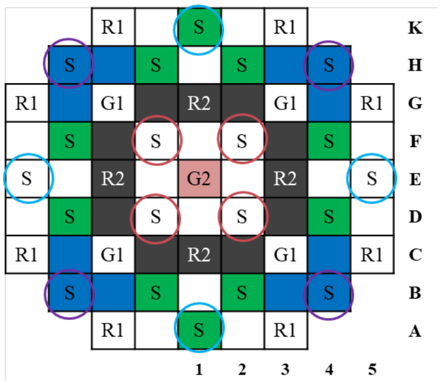


Figure 2. CEA Pattern of ATOM

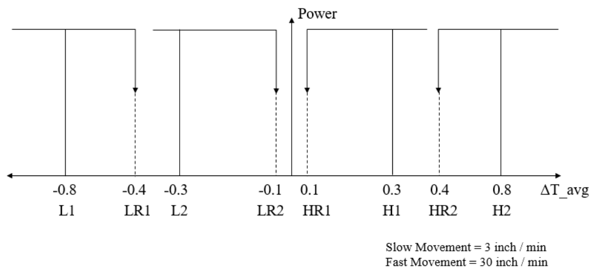
Table 1. Detailed Description on CEA Composition

S	Shutdown bank (24 fingers)
S	Extended shutdown bank (30 fingers)
S	Extended shutdown bank (33 fingers)
S	Extended shutdown bank (36 fingers)
R1	Regulating bank type 1 (50% B_4C)
R2	Regulating bank type 2 (Nat. B_4C)
G2	Gray bank (SS-cladded Mn)
G1	Gray bank (Inconel 625)

3. CEA Control Logic Mode-Y

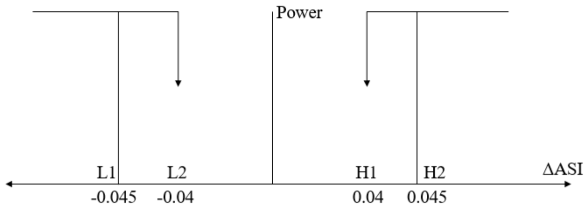
The Mode-Y logic automatically controls the movement of each control element assembly to obtain targeted reactor core power and axial shape index simultaneously. It was firstly introduced in 2019, now it has several features including part-length control rod consideration through continuous developments [4]. It determines the direction of control rod movements and the speed of movements with the temperature dead-band and the difference between target and measured coolant temperature, its corresponding temperature dead-band and stage flag logics are illustrated in Figure 3. If the temperature or ASI is out of the dead-band, the Mode-Y logic moves the control rods of selected CEAs until it restores those quantities into the dead-band with some sufficient margin so that the core maintains the normal flag for sufficiently long time.

The ASI control is considered when the coolant temperature is within the dead-band because the temperature management is the most important in the load-follow operations. It takes into account the relatively simple physics that the changes in ASI are opposite when the control rods move in the upper and lower half of the core. A special consideration in the Mode-Y logic is that it excluded the overlapping between gray rods which are expressed in G2 and G1 for more effective ASI control, which means that the gray rods can move independently. The ASI dead-band and stage flag logic is explained in Figure 4 and overall CEA selection logic according to the stage flags are listed in Table 2.



Old Flag	ΔT_avg	New Flag
Normal	H1 < ΔT_avg L2 < ΔT_avg < H1 ΔT_avg < L2	Insert Normal Cold
Insert	H2 < ΔT_avg HR1 < ΔT_avg < H1 ΔT_avg < HR1	Fast Insert Insert Normal
Fast Insert	HR2 < ΔT_avg ΔT_avg < HR2	Fast Insert Insert
Withdraw	ΔT_avg < L1 L2 < ΔT_avg < LR2 LR2 < ΔT_avg	Fast Withdraw Withdraw Normal
Fast Withdraw	ΔT_avg < LR1 LR1 < ΔT_avg	Fast Withdraw Withdraw

Figure 3. Temperature Dead-band and Stage Flag Logic



Old Flag	ΔASI	New Flag
AAS	H2 < ΔASI L1 < ΔASI < H2 ΔASI < L1	UARS+ AAS UARS-
UARS+	H1 < ΔASI L1 < ΔASI < H1 ΔASI < L1	UARS+ AAS UARS-
UARS-	H2 < ΔASI L2 < ΔASI < H2 ΔASI < L2	UARS+ AAS UARS-

Figure 4. ASI Dead-band and Stage Flag Logic

Table 2. CEA Selection Logic

Direction	ASI Flag	CEA Position	Selected CEA	Effect
Insert	UARS+	G2 > B G2 = B, G1 > B G2 = B, G1 = B	G2 G1 R2	P If G2 < H/2 P If G1 < H/2 I

	UARS-	G2 > H/2
		G2 < H/2, G1 > H/2
		IF (G2 < H/2, G1 < H/2) THEN
		IF (R2 > H/2) THEN
		
		ELSE
		IF (G2 > B) THEN
		ELSE IF (G1 > B) THEN
		END IF
		END IF
			G2
			G1
			
			R2
			
			G2
			G1
				P
				P
				
				P
				
				N
				N

	AAS	G2 > B G2 = B, G1 > B G2 = B, G1 = B	G2 G1 R2	P If G2 < H/2 P If G1 < H/2 I
Direction	**ASI Flag**	**CEA Position**	**Selected CEA**	**Effect**
Withdraw	UARS+	R2 < UL R2 = UL, G1 < UL R2 = UL, G1 = UL	R2 G1 G2	P If R2 > H/2 P If G1 > H/2 P If G2 > H/2
	UARS-	R2 < UL R2 = UL, G1 < H/2 R2 = UL, G1 = H/2, G2 < H/2 R2 = UL, G1 = H/2, G2 = H/2 R2 = UL, G1 = UL, G2 = H/2	R2 G1 G2 G1 G2	P If R2 < H/2 P P N N
	AAS	R2 < UL R2 = UL, G1 < UL R2 = UL, G1 = UL	R2 G1 G2	P If R2 > H/2 P If G1 > H/2 P If G2 > H/2

4. Numerical Results

The numerical results for load-follow operations at different three burnups are analyzed. The reactor core burnups at 0GWd/MTU for the beginning of cycle (BOC), 10GWd/MTU for the middle of cycle (MOC), and 18GWd/MTU for the end of cycle (EOC) are used in this paper and all simulations start at the hot full power Xe-135 and Sm-149 equilibrium state. The constant average coolant temperature strategy was given to the simulations. The steam generator was decoupled, so it was assumed that the inlet coolant temperature accurately varies with respect the demand power.

The total simulation time is 72 hours and time step is 2 secs. During the power ramp up and down, the reactor power changes 1.6% of rated power per minute (50% of rated power per 30 minutes) and control rod movements for these changes were regulated by the Mode-Y logic.

The burnup-dependent numerical results including core power variation, CEA height from bottom of the core, ASI, and peaking factors during the load-follow operation are illustrated from Figure 5 to Figure 16. It can be seen that the core power follows the demand power within the temperature dead-band for all burnup cases. In addition, peaking factors and ASI values remain within acceptable ranges during the whole simulations.

4.1 Load-Follow Operation at BOC

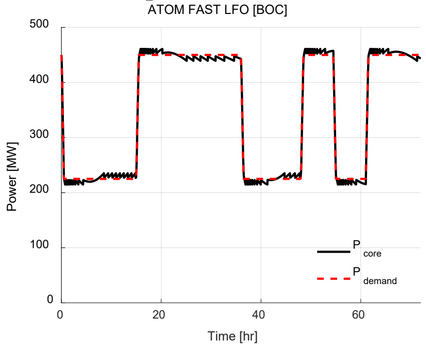


Figure 5. Demand Power vs. Core Power at BOC

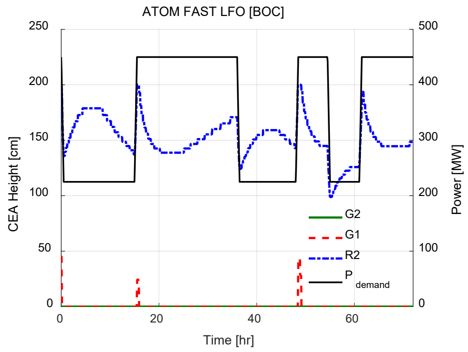


Figure 6. CEA Position at BOC

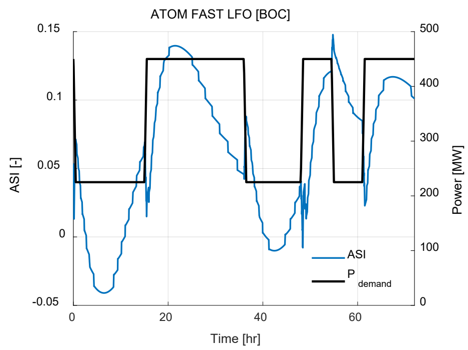


Figure 7. ASI at BOC

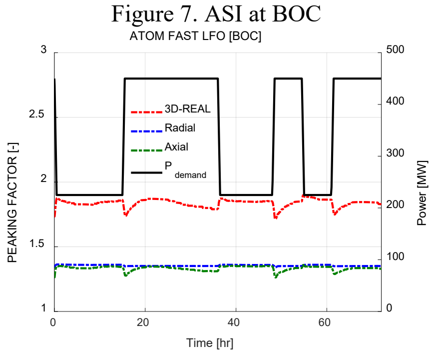


Figure 8. Peaking Factors at BOC

4.2 Load-Follow Operation at MOC

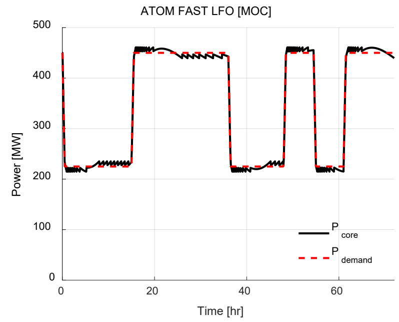


Figure 9. Demand Power vs. Core Power at MOC

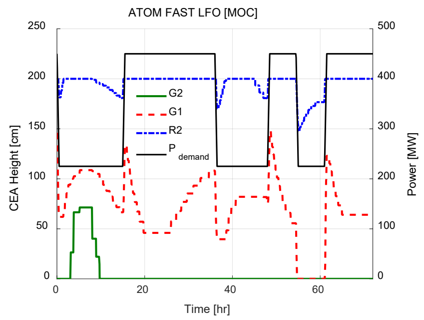


Figure 10. CEA Position at MOC

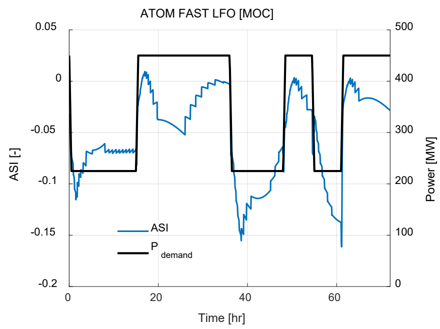


Figure 11. ASI at MOC

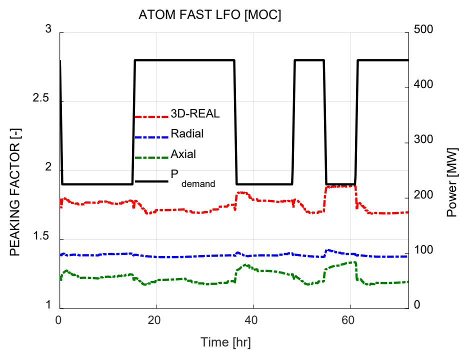


Figure 12. Peaking Factors at MOC

4.3 Load-Follow Operation at EOC

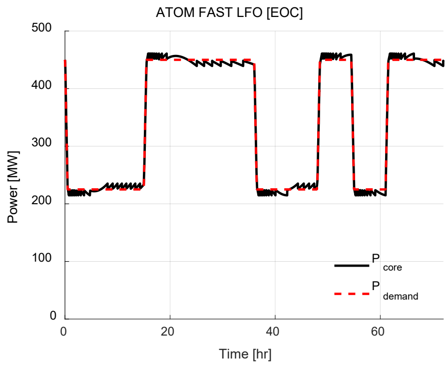


Figure 13. Demand Power vs. Core Power at BOC

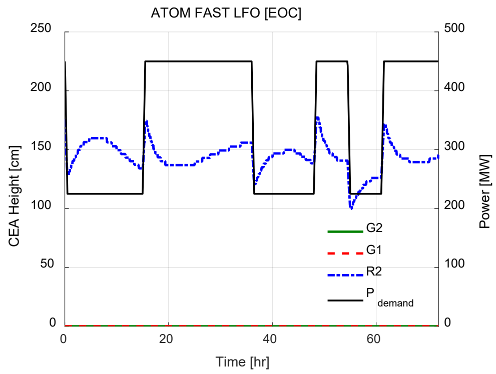


Figure 14. CEA Position at EOC

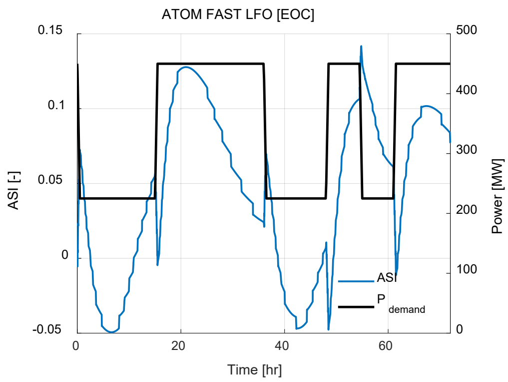


Figure 15. ASI at EOC

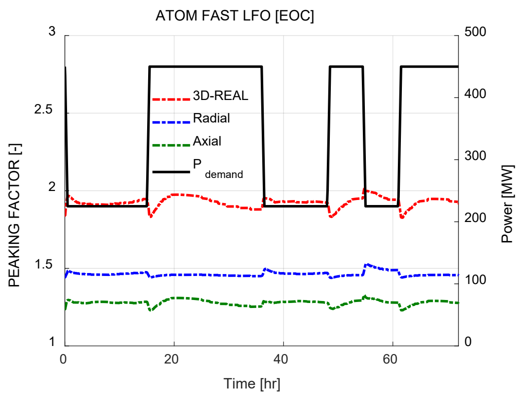


Figure 16. Peaking Factors at EOC

5. Summary and Conclusions

In this study, the power maneuvering availability of the ATOM core with control was investigated at various burnup conditions by using the in-house nodal code KANT. The programmed inlet coolant temperature is used for the constant average coolant temperature strategy and CEAs are controlled by the Mode-Y logic. It was found that the core power is well controlled during 72 hours of simulations through all burnup points even though the power change rate is relatively fast. Also, the ASI value in the simulations remain within acceptable range with the ASI control. Especially, the ASI control can be easily observed at the MOC case which shows the independent movement of gray rods during the simulation by Mode-Y logic. From those numerical results, it can be inferred that Mode-Y logic can successfully operate the load-follow situations of the soluble-boron-free reactor core ATOM.

For the future works, some improvements about the Mode-Y logic will be implemented such as a function that moves two control rods simultaneously in opposite directions to get more stable axial power profile. Moreover, the pin power distribution of the hottest node can be reconstructed with the embedded pin power reconstruction method.

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