# Multi-Physics Simulation for Load Follow Operation

*Abd El Rahman Mahmoud[1,*] and Aya Diab[1,2,†]*
[1]*Nuclear Engineering Department, KEPCO International Nuclear Graduate School, Ulsan, South Korea,*
[2]*Mechanical Power Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt.*
[*]*First Author Email: aelala@kings.ac.kr | abdelrahman.m.hassan@gmail.com*
[†]*Corresponding Author Email: aya.diab@kings.ac.kr | aya.diab@eng.asu.edu.eg*

## 1. Introduction

All nuclear power plants in South Korea are operated at a baseload mode, that is 100% rated power, and do not employ power tracking control except for startup, shutdown, and during transients. However, as the electrical energy generated from nuclear power plants represents a significant portion of the total energy mix, load follow operation (LFO) may be needed to cover the imbalance between consumption and production [1]. Additionally, the load-follow operation of nuclear power plants may be essential to balance the intermittent nature of plants relying on renewable energy sources such as wind, solar.

NPPs must therefore adapt to those load demand variations. Unlike traditional thermal power plants, load follow operation may be quite challenging for NPPs. The difficulty arises from the fact that the operators, need to control the axial power distribution and core reactivity at the same time as they conduct the power maneuvering [2].

In this work, a multi-physics simulation is undertaken to reflect the impact of feedback signals on the system safety parameters during power maneuvering.

## 2. The Korean Mode-K for Load Follow Operation

Mode-K is an advanced reactor control logic algorithm that was developed in the 1990s [3, 4]. This mode uses boron with both regulating (R-bank) and heavy-worth control (H-bank) banks in controlling the reactor during LFO.

The R-bank and boron are used to control core reactivity (xenon, power defect, reactor average temperature) and the H-bank is used to control the axial power shape.

It is worth noting that Mode-K utilizes H-bank dedicated to axial power distribution control independently of the existing R-banks. Therefore, it is possible to control the axial shape index (ASI) by providing a monotonic relationship between the motion of H-bank and ASI represented by Equation(1):

$$ASI = \frac{P_b - P_t}{P_b + P_t} = -AO \qquad (1)$$

where $P_b$ and $P_t$ are the normalized power of bottom and top halves of the core, respectively, and AO is the core axial offset.

In Mode-K, the degree of ASI deviation from the target ASI, determines the control rod bank or banks to be used according to the following stage flags:

1. ORS (Overlap Restoring Stage),
2. FOS (Fixed Overlap stage) and
3. ARS (ASI Restoring Stage)

The reactor regulation system (RRS) selects a bank or banks by using the deviation of ASI as represented by the stage flags. Fig. 1 shows the concept of how to switch the stage flag.

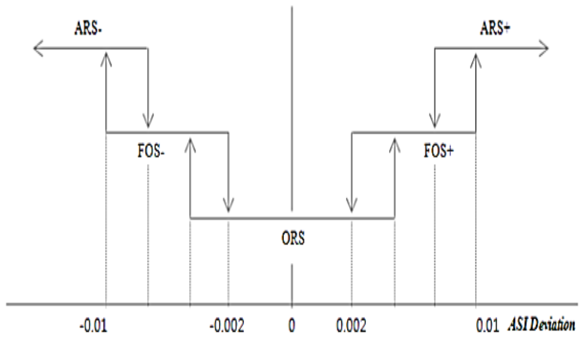


Fig. 1. Stage Flag Concept for ASI control [3]

## 3. Computer Code System

A number of research studies focused on load follow simulations have been published and can be summarized as follows [5, 6, and 7]:

1. Simulations using only reactor physics codes with no feedbacks from primary or secondary loop systems.
2. Coupling the reactor physics codes with simple lumped models that describe both primary and secondary circuits.

In this study, a load follow simulation is conducted using a multi-physics approach through the multi-physics code, RELAP5/SCDAPSIM/MOD3.4/3DKIN package [8] to simulate Mode-K strategy.

This package is capable of modeling the three-dimensionality of the LFO, while simultaneously taking into account the feedback mechanisms.

RELAP5/SCDAPSIM/MOD3.4/3DKIN package is developed by a US-based company, Innovative Systems Software (ISS). This package consists of three main independent codes, implicitly coupled using an internal coupling type and serial integration approach.

The three codes are:

- **RELAP5**, Reactor Excursion, and Leak Analysis Program, is a thermal-hydraulics system code developed by Idaho National Laboratory (INL).
- **SCDAPSIM**, Severe Core Damage Analysis Package Simulator, is a severe accident code developed by INL.
- **3DKIN**, 3 Dimension Kinetics, is a neuron kinetics code base on NESTLE [9] code that is developed by North Carolina State University (NCSU) for Electrical Power Research Institute (EPRI).

In this study, we will focus only on Neutronics and Thermal-Hydraulic (NK/TH) modules, i.e. between RELAP5/MOD3.4 and 3DKIN within RELAP5/SCDAPSIM/MOD3.4/3DKIN. As mentioned earlier, this multi-physics package relies on an internal coupling with serial integration as illustrated in Fig. 2.

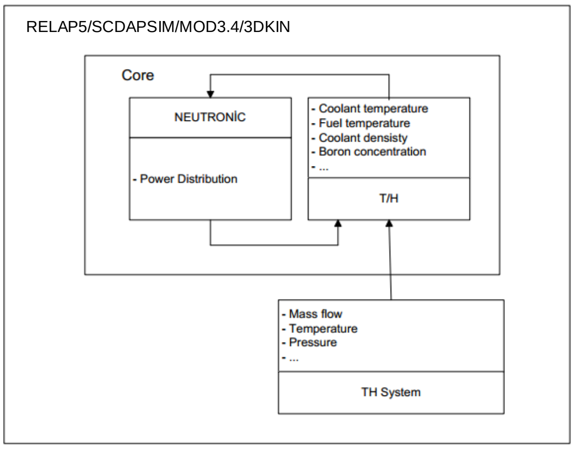


**Fig. 2. Data Exchange in Coupling Neutronics and Thermal Hydraulics Modules**

## 3. Simulation of Load Follow Operation

### *3.1 APR1400 System Description*

In this study, an equilibrium core of APR1400 is loaded with 16×16 PLUS7 fuel assemblies in 3 batches. The cycle length is 475 EFPDs. APR1400 system nodalization, shown in Fig. 3, describes the major thermal-hydraulic components within the plant. Fig. 6

### *3.2 Daily Load Follow Operation of APR1400*

The simulation of the daily load follow operation has been performed according to the power maneuvering scenario shown in Fig. 4. The power change to 100% to 50% over a period of 3 hours, maintained at 50% for 6 hours, before it is ramped up to 100% over 3 hours and then maintained at 100%.

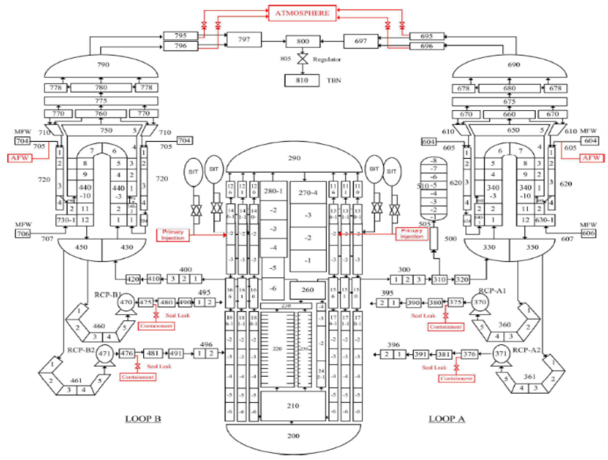


**Fig. 3. APR1400 System Nodalization**

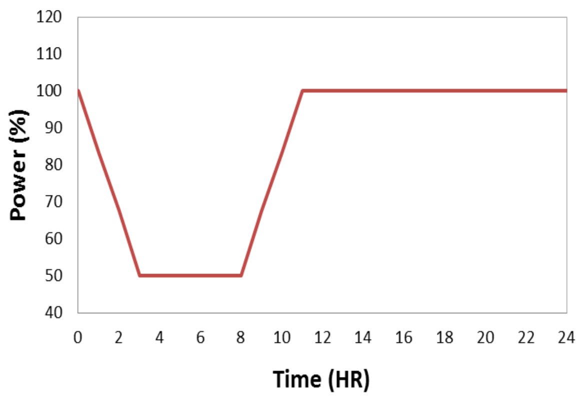


**Fig. 4. MODE-K Daily Load Follow Scenario**

The reactor power is controlled with R-banks, H-banks, and soluble boron to meet the daily LFO requirements. The proper combination of the position of each control bank, as well as the boron concentration, is determined to maintain the critical state while simultaneously satisfying several operating limits such as the axial offset (AO).

## 4. Results

The model results obtained via the multi-physics simulation are presented in this section. The data obtained are organized under neutronics and thermal-hydraulics results.

### *4.1 Core Neutronics Parameters*

To follow the load, the Control Element Assemblies (CEAs) are used to control the reactor power. CEAs insertion positions in percent are shown in Fig. 5.

The boron concentration is also used in Mode-K to control the reactor power as shown in Fig. 6.

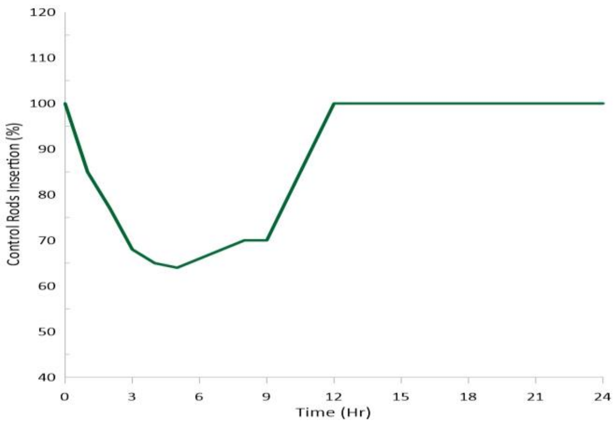


**Fig. 5. Control Rod Bank Normalized Insertion Length**

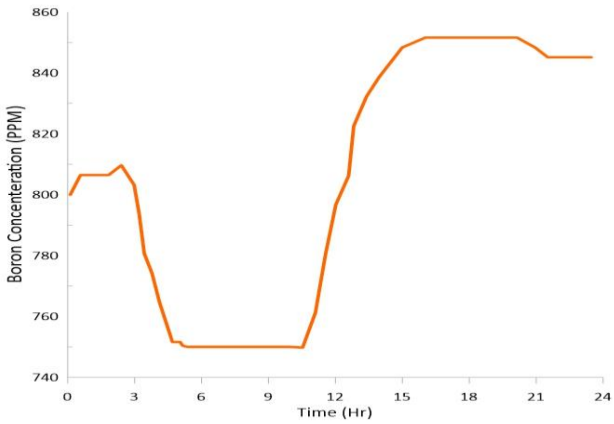


**Fig. 6. Boron Concentration**

As shown in Fig. 5 and Fig. 6, the CEAs lead the power change from 100% to 50% within 3 hours by inserting them in the reactor core while keeping the boron concertation unchanged. After 3 hours the boron concentration is decreased allowing the core reactivity to reach a stable condition. After 9 hours the CEAs are withdrawn to increase the power while the boron concentration increases to maintain an almost zero positive reactivity and suppress any excess positive reactivity until the core reaches its critical state.

One of the important parameters during LFO is the core axial offset (AO) which is defined by Equation (1) and plotted as a function of time in Fig. 7.

The AO is always negative and its values during one load cycle are within the limit defined by the Core Operating Limits Report (COLR) which is ±0.27.

*4.2 Primary Thermal-Hydraulics Parameters*

The reactor pressure vessel (RPV) inlet (cold legs) temperatures, Fig. 8, and pressurizer collapsed water level, Fig. 9, are selected to be the primary thermal-hydraulic parameters that represent the system's response to the power change scenario.

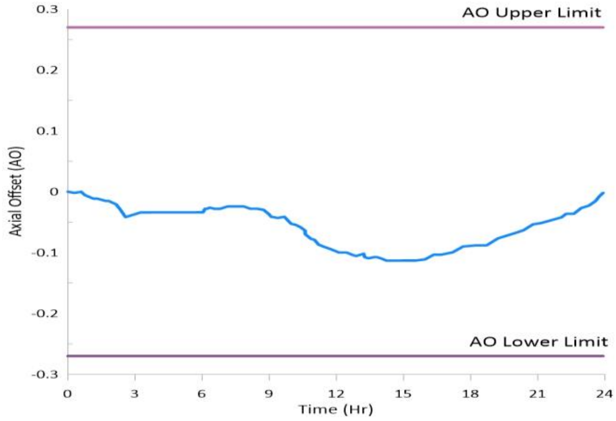


**Fig. 7. Axial Offset versus Time**

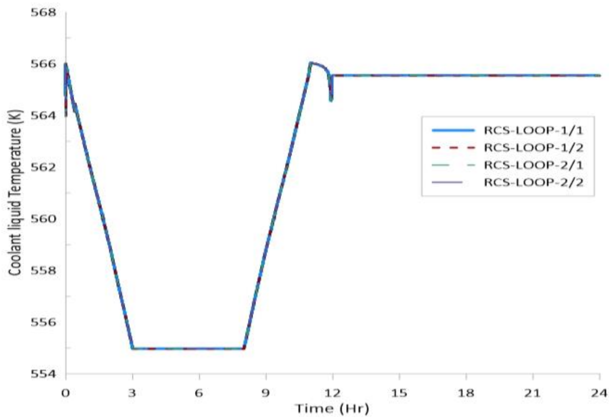


**Fig. 8. Reactor Coolant System Cold Leg Temperatures**

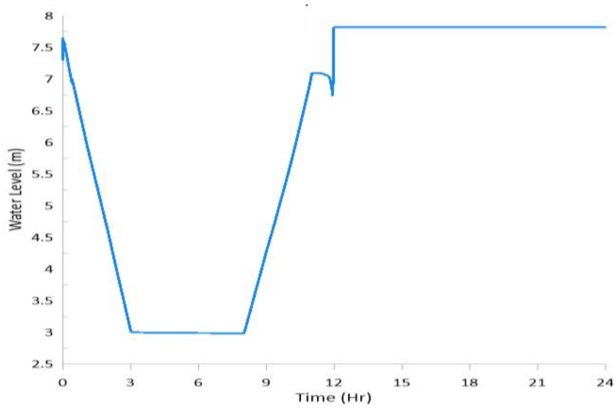


**Fig. 9. Pressurizer Collapsed Water Level**

The parameters represented by Fig. 8 and Fig. 9 are identically following the power load change except when returning to 100% power due to fluctuations in the steam generators prior to reaching steady-state.

*4.3 Secondary Thermal-Hydraulics Parameters*

The steam generators (SG) pressure and collapsed water level are the main parameters of interest to represent the LFO on the secondary side.

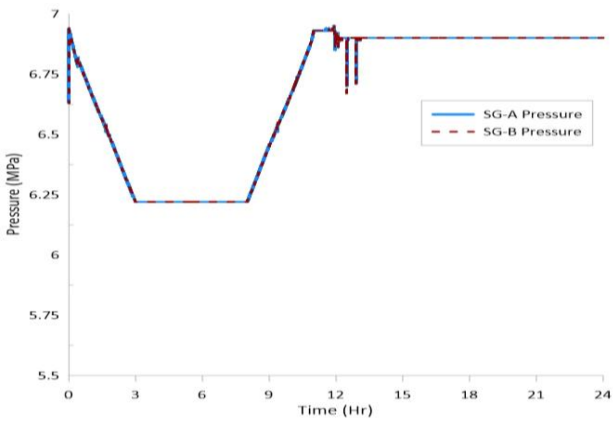


**Fig. 10. Steam Generators Pressure**

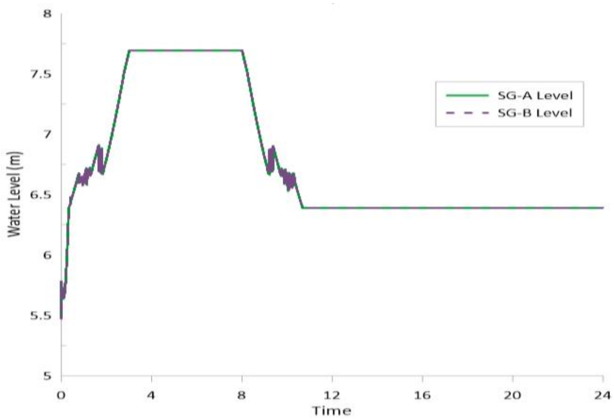


**Fig. 11. Steam Generators Collapsed Water Level**

Fig. 10 represents the pressure inside the steam dome. The pressures are identically following the power load change except for the period when the pressures are restored from 50% to 100% power load. These pressure oscillations are the main reason for the oscillations in the RCS cold leg temperatures and pressurizer water level.

Fig. 11 represents the collapsed water level of the two SGs. The water levels are inversely proportional to the power load change. When the power is decreased the SGs water levels increase because there is less steam generated inside the SGs while they decrease during restoring the power from 50% to 100% as more steam is generated.

### 5. Conclusions

A multi-physics simulation is performed to analyze APR1400 plant response to the daily LFO. The main advantage of using the multi-physics simulation is the ability to model and simulate very complex physical processes that occur inside the reactor core.

It is demonstrated that the multi-physics LFO could successfully meet all design criteria. The maximum 3D pin peaking factor ($F_q$) is 2.176 at 100% and 2.587 at 50% during the tested cycle length, and the maximum negative AO is -0.146.

For future work, this tool could be used to analyze the system during LFO in case of ATWS with different power rates change.

### Acknowledgments

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### REFERENCES

[1] A. Lokhov, “Technical and Economic Aspect of Load Following with Nuclear Power Plants”, Nuclear Energy Agency, OECD, June 2011.

[2] F. Yousefpour, M. B. Ghofrani, “Improvement of Axial Power Distribution Control Capabilities in VVER-1000 Reactors”, Annals of Nuclear Energy 27, pp.949-957, 2000.

[3] S. Y. Oh, J. H Chang, AND J. K. Park, Mode K - A Core Control Logic for Enhanced Load-Follow Operations of A Pressurized Water Reactor, Nuclear Technology, Vol.134, May 2001.

[4] J. I. Choi, S. Y. Oh, AND J. E. Kuh, Advanced Load Follow Operation Mode for Korean Standardized Nuclear Power Plants, Journal of Korean Nuclear Society Volume 24, Number 2, June 1992.

[5] M. Park, J. Choe, D. Lee, E. Lee, “Application of RAST-K to Simulation of OPR1000 Daily Load Follow Operation”, Transactions of the Korean Nuclear Society Autumn Meeting, Pyeongchang, Korea, October 30-31, 2014.

[6] M. Park, J. Choe, D. Lee, E. Lee , “Verification of RAST-K Capability for Simulation of OPR1000 Daily Load Follow Operation by Mode K”, Transactions of the Korean Nuclear Society Autumn Meeting, Pyeongchang, Korea, October 30-31, 2014.

[7] Fuyu Zhao et. al., “Modeling and load follow simulation of CPR1000 Nuclear Power Plant implementing Mechanical Shim control strategy”, Nuclear Engineering and Design 352 (2019).

[8] ISS, RELAP/SCDAPSIM/MOD3.x User Reference Manual, Volume I: “Advanced Fluid Systems Thermal Hydraulics Analysis”, Volume II: “LWR Fuel Assembly, Core, and Plenum Structure Analysis Under Normal and Accident Conditions”, Volume III: “Reactor Systems Modeling Options - Reactor Kinetics”, Innovative Systems Software, 3585 Briar Creek Lane, Ammon Idaho 83406 (2019).

[9] North Carolina State University; “NESTLE Version 5.2.1; Few-Group Neutron Diffusion Equation Solver Utilizing The Nodal Expansion Method for Eigenvalue, Adjoint, Fixed-Source Steady-State, and Transient Problems”; Electric Power Research Center; North Carolina (2003), USA.