

Three-D TH-coupled Simulation of Load-follow Operation in a Low-boron APR1400

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1. Introduction

This paper describes the on-going work for developing three-dimensional simulator of load-follow operation in a low-boron APR1400 design [1]. The low-boron APR1400 design is achieved by utilizing the centrally shielded burnable absorber (CSBA) [2, 3]. The developed algorithm selects the control element assembly (CEA) to be adjusted and its direction of movement. It also performs criticality search for the critical heights of the CEAs and the critical boron concentration (CBC). The simulation's goal is to find the critical heights and CBC during the load-follow so that distortions of the axial and radial power distributions can be minimized while maintaining the programmed coolant temperature strategy.

The control rod pattern used in this study is similar to the standard pattern for the APR1400 reactor. As demonstrated in Fig.1, it utilizes 5 regulating banks that are full-strength CEAs and 2 groups of part strength CEAs (PSCEAs). The relatively weak worth of the PSCEAs provides flexible means of reactivity control, especially for maintaining acceptable axial power profile during the load-follow operations. Figure 2 illustrates the design of a rodged APR1400 fuel assembly along with control rod configuration. Results of this work show a successful load-follow operation in the low-boron APR1400 using the two PSCEAs and the leading regulating bank (R5).

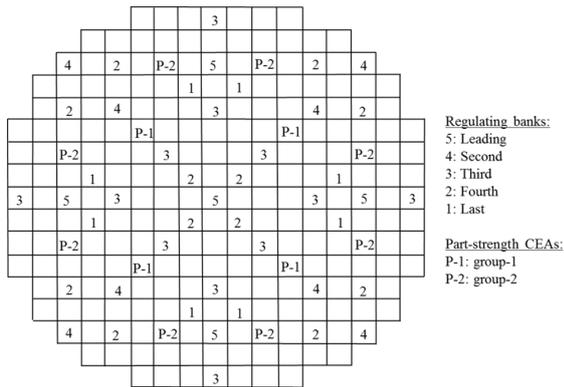
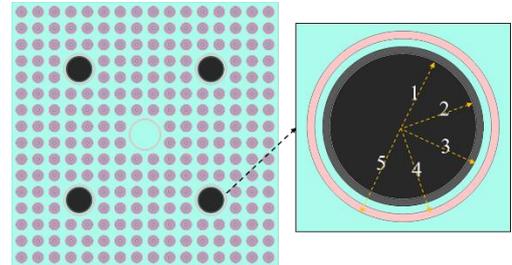


Fig. 1. Control rods pattern

2. Methods

The neutronic solution is based on the two-step procedure. The various cross-sections and sensitivity coefficients are obtained using Serpent-2 Monte Carlo simulations with ENDF/B-VII7.1. The whole core

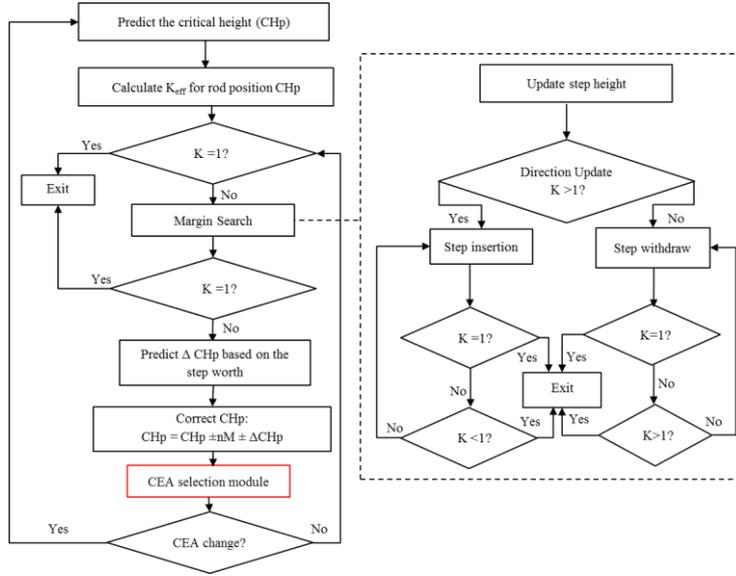
solution neutronic solution is based on 3-D NEM with assembly discontinuity factor. The neutronic solution is coupled with thermal-hydraulic (TH) solution in all fuel assembly channels and transient Xe and Sm models. The dependence of the various cross-sections (XSs) on the variation of burnup (Bu), fuel temperature (T_f), moderator temperature (T_m), moderator density (D_m), and soluble-boron concentration (Sb) is considered by applying Eq. (1). The whole core neutronic and TH models are solved by an in-house FORTRAN-95 code. The quasi-static approach is used, because the code was developed to obtain the critical CEA height and CBC at steady-state for a given programmed inlet coolant temperature with power. Thus, the 3-D neutronic-TH coupled solutions treated as steady-state. However, time-dependent calculations of Xe and Sm concentrations are obtained by solving the time-dependent equation of the decay chains of the decay chains of Xe-135, I-135, Pm-149 and Sm-149 [4]. The algorithm for of the 3-D multi-physics code with criticality search using control rods is demonstrated in Fig.3.



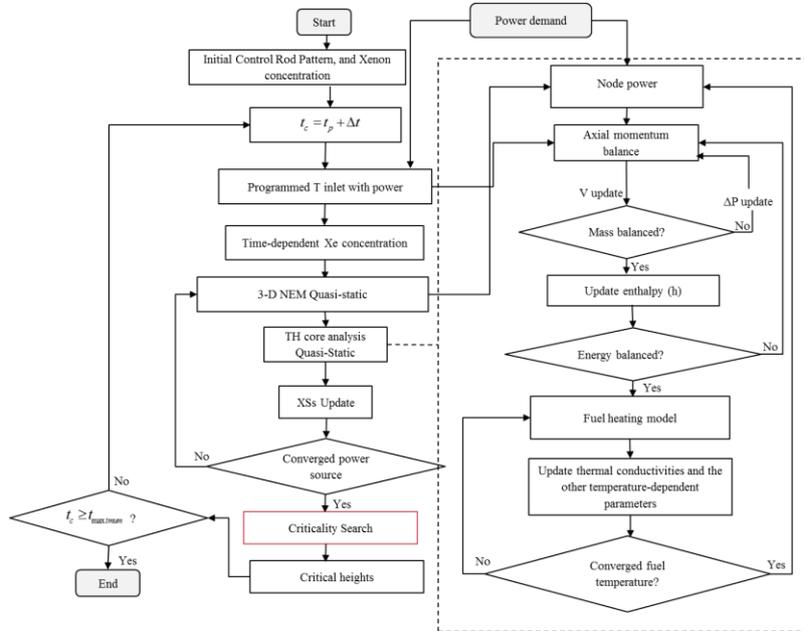
No.	Radius (cm)	Material
1	0.93599	- B ₄ C (Full strength CEA) - Inconel-625 (Part strength CEA)
2	0.94742	Air
3	1.03632	Inconel-625
4	1.13764	Water
5	1.23949	Zry-2

Fig. 2. Control rods configuration

$$\begin{aligned}
 & \Sigma_a(Bu, T_f, T_m, D_m, S_b) \\
 & = \Sigma_a^{ref}(Bu) + \frac{\partial \Sigma_a}{\partial \sqrt{T_f}} \Delta \sqrt{T_f} + \frac{\partial \Sigma_a}{\partial T_m} \Delta T_m \\
 & + \frac{\partial \Sigma_a}{\partial D_m} \Delta D_m + \frac{1}{2} \frac{\partial^2 \Sigma_a}{\partial D_m^2} (\Delta D_m)^2 \\
 & + N_{Hom}^{Xe, \infty}(\phi_g) \sigma_a^{Xe}(Bu, T_f, T_m, D_m, S_b) \\
 & + N_{Hom}^{Sm, \infty}(\phi_g) \sigma_a^{Sm}(Bu, T_f, T_m, D_m, S_b) \\
 & + N_{Hom}^{B10}(D_m, S_b) \sigma_a^{B10}(Bu, T_f, T_m, D_m, S_b),
 \end{aligned} \tag{1}$$



a) Criticality search module



b) 3-D Multi-physics code algorithm

Fig. 3. Algorithm of the 3-D multi-physics code with criticality search using control rods

In the numerical simulations, the power demand is given along with the core inlet coolant temperature strategy with the reactor power variation. In this paper, we simulate the conventional constant inlet coolant temperature strategy with power. The Xe and Sm concentrations are solved using the discretized time-dependent Eqs. 2-3.

$$N_{Xe}(t_n + \Delta t) = N_{Xe}(t_n) + \Delta t (\lambda_I N_I(t_n) + \gamma_{Xe} \sum_{g=1}^G \sigma_{f,g}(t_n) \phi_g(t_n)) \quad (2)$$

$$- \lambda_{Xe} N_{Xe}(t_n) - \sum_{g=1}^G \sigma_{Xe,a,g}(t_n) N_{Xe}(t_n) \phi_g(t_n)$$

$$N_{Sm}(t_n + \Delta t) = N_{Sm}(t_n) + \Delta t (\lambda_{Pm} N_{Pm}(t_n)) \quad (3)$$

$$- \sum_{g=1}^G \sigma_{Sm,a,g}(t_n) N_{Sm}(t_n) \phi_g(t_n)$$

Three-dimensional NEM calculations with assembly discontinuity factor (ADF) is made with 1x1 discretization in the radial direction and a non-uniform discretization in the axial direction. The NEM solution is coupled with Xe and Sm feedback and the whole core TH feedbacks. The TH module is based on the single-channel methodology, i.e., no crossflow is considered. Therefore, the basic governing balance equations of mass, energy, and axial momentum equations are solved. For each axial node, the fuel heat transfer module solves the heat conduction equation in the radial direction for discretized nodes using finite-difference method. Non-linear iterations are performed until a converged temperature distributions are obtained, as demonstrated in Fig. 3-b. It should be noticed that the NEM algorithm

solves the whole core calculation as an eigenvalue problem. If K_{eff} deviates from unity with more than 10 pcm, a criticality search is made using the control rods for a user defined CBC. The movement of the CEAs and the variation of the CBC must maintain acceptable values of the axial shape index (ASI) and the programmed coolant temperature variation. This requires a control logic to select the CEAs to be moved and the directions of movement based on the deviations of the ASI and the programmed coolant temperature change. However, the development of the control algorithm is still on-going, therefore, the selection of the CEAs and their direction of movement is defined by the user in this work.

The control rod criticality search module illustrated in Fig. 3-a is named as “worth-margin” control rod search scheme. At first, we find the predicted critical height (CHp) based on the selected CEA or CEAs worth. The first multi-physics calculations is made based on that predicted value. If $|K_{eff} - 1| > 10$ pcm, the margin search is made. The goal of the margin search module is to reduce the search margin and to correct the CHp. In the margin search, the direction of movement is based on the K_{eff} value. The length of the step insertion (M) is a user defined parameter, at first, M should be appropriately large for faster search. The searched steps are $n*M$ where $n = 1, 2, 3$, etc. After the completion of the margin search, if $|K_{eff} - 1| > 10$ pcm, ΔCHp is found based on the latest CEA step worth. The CHp value is then updated knowing the CEA depth at the end of the margin search (L_m) and ΔCHp , as illustrated in Eqs. 4-5. ΔCHp is added or subtracted based on K_{eff} value after the margin search.

$$CH_p^{new} = L_m \pm \Delta CH_p \quad (4)$$

$$L_m = CH_p^{old} \pm n * M \quad (5)$$

3. Results and Discussions

In this study, numerical simulations of a typical 100-50-100 load-follow operation is performed. In the simulation, the reactor power ramp up/down is achieved in 3 hrs. The study is made for a low-boron APR1400 design, where the CBC at BOC is 455 ppm. The low-boron APR1400 design is made by utilizing the CSBA burnable absorbers with non-uniform axial loading of the CSBA to achieve a rather balanced axial power distribution. This is because the axial power shape is bottom skewed in a low-boron boron pressurized water reactor (PWR) due to the strongly negative moderator temperature coefficient (MTC). The numerical simulations are performed for a fresh core at BOC after Xe equilibrium. The two groups of the PSCEAs are inserted to the middle of the active core region during the hot full power (HFP) operation. This allows a flexible axial shape index (ASI) control during the load-follow operation. In Fig.4, the variations of Xe concentration and core power are plotted together. Since the reactor is initially at Xe-equilibrium, Xe concentration begins to slowly increase during the ramp-down period. The Xe-induced reactivity feedback during the 1st power ramp-down period is enhancing the power ramp-down. In

addition, in the power ramp-up period, Xe concentration slowly decreases. The decrease of Xe concentration yields a positive reactivity feedback. Figure 5 illustrates the variation of core coolant temperature. In addition, Figures 6-8 illustrate the critical heights of first and second PSCEAs groups (P1 and P2), the critical height of the leading and the second regulating banks (R5 and R4), and the variation of CBC, respectively.

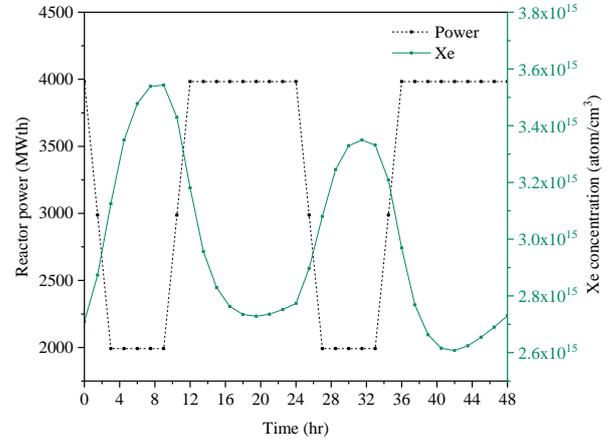


Fig. 4. Core power and Xe concentration

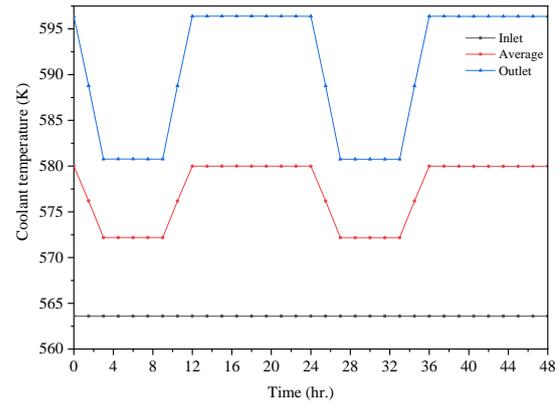


Fig. 5. Core coolant temperature variation

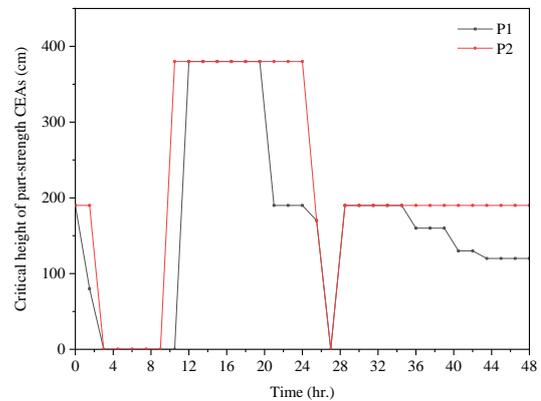


Fig. 6. Adjustment of part-strength CEAs

As the reactor power starts to decrease, the fuel temperature decreases following the change in the reactor power. Since FTC is slightly negative in the core,

a positive fuel-induced reactivity feedback occurs due to the power ramp-down[5]. Meanwhile, for a programmed constant inlet temperature strategy, the core average coolant temperature follows the variation of the reactor power, as shown in Fig. 5. Therefore, as the reactor power starts to decrease, a positive coolant-induced reactivity feedback occurs due to the negative MTC.

The adjustments of P1, P2, R5, R4, and CBC are made to maintain the programmed variation of the average coolant temperature and allowable ASI values. Figure 9 demonstrates rather small variation of the ASI during the load-follow operation. Figure 10 demonstrates the variation of the core axial power distribution for selected time steps. It is clear that these deviations are rather limited due to the active control of the power shape using the part and full strength CEAs and the CBC.

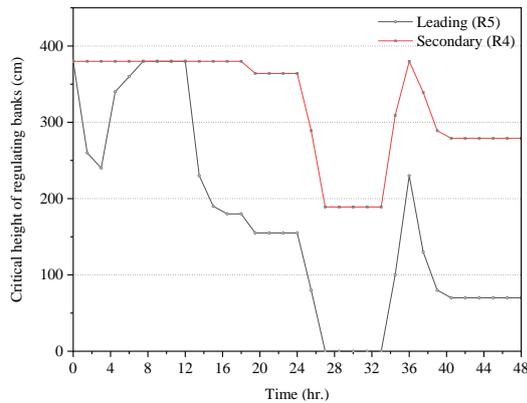


Fig. 7. Adjustment of the leading regulating CEAs

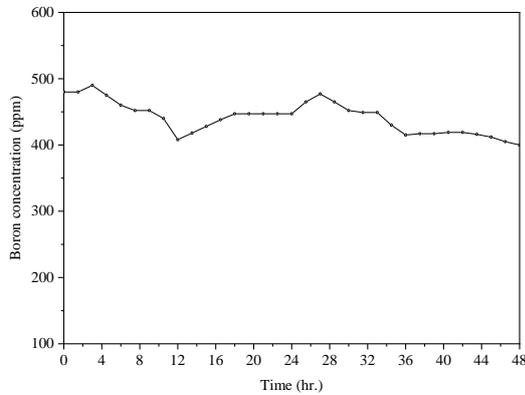


Fig. 8. CBC adjustment

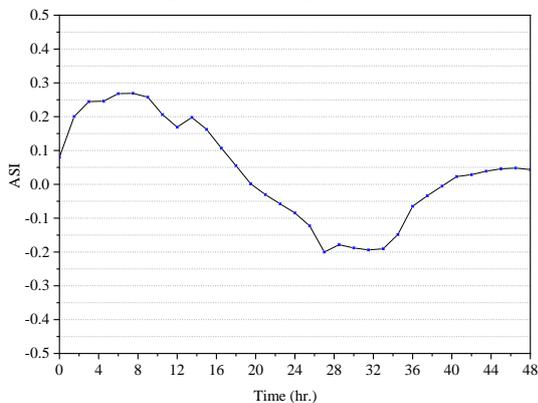


Fig. 9. ASI variation

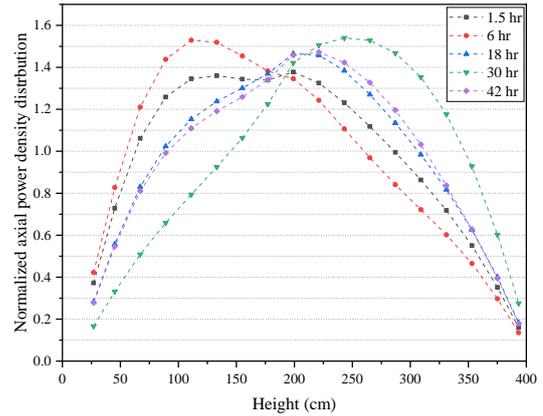


Fig. 10. Variation of the axial power distribution

4. Conclusions

An in-house 3-D multi-physics code coupled with time-dependent Xe and Sm has been developed for simulating a typical daily load-follow operation in a low-boron APR1400 design. The in-house code includes criticality searches for finding the critical heights of the two part-strength CEA groups (P1 and P2), and the leading and second regulating banks (R5 and R4) for a user-defined critical boron concentration (CBC). The selection of the CEAs and the variation of CBC is made to maintain acceptable axial shape index variation and the programmed change of the coolant temperature with the reactor power. In the current work, a user-defined selection of the CEA is required during the simulation. On-going researches are currently made to develop a control logic for the CEAs selection.

ACKNOWLEDGEMENTS

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