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Feasibility of Cold Nuclear Startup in Autonomous Soluble-Boron-Free SMR

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1. Introduction

A nuclear reactor is a complex system that requires highly sophisticated controllers to ensure that desired performance and safety can be achieved and maintained during its operations. Higher-demanding operational requirements such as reliability, lower environmental impacts, and improved performance under adverse conditions in nuclear power plants, coupled with the complexity and uncertainty of the models, necessitate the use of an increased level of autonomy in the control methods [1]. Due to strong thermal and xenon reactivity feedbacks in thermal reactors, it is more challenging to design an autonomous PWR type SMR than designing an autonomous fast SMR(such as the proposed designs of 4S [2] and SSTAR[3] fast SMRs). Autonomous reactivity control in fast reactors is studied in reference [4].

Many designs of water cooled SMRs (such as NuScale [5], SMART [6], ACP-100[7], and KLT-40S [8]) use soluble boron for reactivity control. However, the use of soluble boron is not favorable for autonomous SMR, because the use of soluble boron requires voluminous recycling systems, these systems require frequent maintenance, which is hardly suitable for the idea of autonomous operation, and operating without soluble boron also eliminates all the boron dilution accidents [9].

One of most challenging design targets of autonomous boron free SMR is to achieve a fast cold startup. In this paper, a simple lumped mathematical model is used to investigate the feasibility of cold nuclear startup of a 300 MWth autonomous soluble-Boron-free small PWR.

2. Methods and Results

In this section, the motivation of this research, the method used, and simulations of cold nuclear start-up procedures are described.

2.1 Motivation

One of the main challenges in autonomous boron free SMR is to achieve an efficient fast cold start up. The conventional method used in large-size PWRs to increase the system temperatures from CZP to HZP values using the reactor pumping system, is quite not suitable for SMRs due to their significantly less reactor surface area which leads to a slow and inefficient cold startup process.

2.2 Mathematical Model

A simple lumped model (figure 1) which included representation for point kinetics, core heat transfer, steam generator heat transfer, and xenon dynamics is used to simulate the cold nuclear start up process.

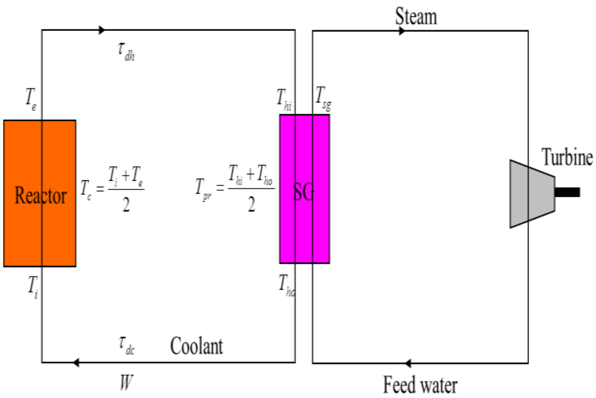

Fig. 1. Simple Lumped Model

The reactor power is modeled using the point kinetics equations with six groups of delayed neutrons and reactivity feedbacks due to changes in fuel temperature, coolant temperature, and xenon concentration in the reactor core. The governing equation of reactivity change is given by:

$$\rho(t) = \rho_0 + \alpha_f \Delta T_f + \alpha_c \Delta T_c + \Delta\rho_{ex} + \Delta\rho_{Xe} \qquad (1)$$

where, α_f is fuel temperature coefficient, α_c is coolant temperature coefficient, ρ_{ex} is the external reactivity, $\Delta\rho_{Xe}$ is xenon induced reactivity change, $\Delta T_f (= T_f(t) - T_{f0})$ is fuel temperature change from initial one, and is coolant temperature change from initial one. Xenon reactivity feedback during transients is proportional to the xenon concentration. Eq. (2) represents xenon reactivity feedback, where ρ_{X0}^{100P} is xenon worth at 100%, and X_0^{100P} is Xenon concentration at 100% power. Eq. (3) represents xenon concentration at time t and Eq. (4) represents Iodine concentration at time t.

$$\Delta\rho_{Xe}(t) = \rho_{X0}^{100P} \frac{X(t) - X_0}{X_0^{100P}}, \qquad (2)$$

$$\frac{dX(t)}{dt} = \gamma_X \Sigma_f \varphi(t) + \lambda_I I(t) - \lambda_X X(t) - \sigma_a^X \varphi(t) X(t) \quad (3)$$

$$\frac{dI(t)}{dt} = \gamma_I \Sigma_f \varphi(t) - \lambda_I I(t) \quad (4)$$

where X (t) is xenon concentration at time t, and I(t) is iodine concentration at time t. The heat balance in the reactor core is given by Eq. (5), (6), and (7) which represent the temperatures of fuel, clad and average coolant temperature. In this model the coolant temperature is considered to be the arithmetic average of inlet and outlet coolant in the core.

$$M_f c_f \frac{dT_f}{dt} = p(t) - \frac{1}{R_g}[T_f(t) - T_{cl}(t)] \quad (5)$$

$$M_{cl} c_{cl} \frac{dT_{cl}}{dt} = \frac{1}{R_g}[T_f(t) - T_{cl}(t)] - \frac{1}{R_c}[T_{cl}(t) - T_c(t)] \quad (6)$$

$$M_c c_c \frac{dT_c}{dt} = \frac{1}{R_c}[T_{cl}(t) - T_c(t)] - 2w(t)c_c[T_c(t) - T_i(t)] \quad (7)$$

where, T_f is fuel temperature, T_{cl} is clad temperature coefficient, T_c is average coolant temperature, M_f is fuel mass, M_{cl} is clad mass, M_c is coolant mass, c_f is fuel specific heat, c_{cl} is clad specific heat, c_c is coolant specific heat, R_g is thermal resistance between fuel and clad, R_c is thermal resistance between clad and coolant, and w(t) is the coolant flow rate. The model also represents the heat balance in steam generator where the average coolant temperature of steam generator is given by:

$$M_{sg} c_c \frac{dT_{pr}}{dt} = w(t)c_c[T_{hi}(t) - T_{ho}(t)] - h_{sg} A_{sg} \Gamma [T_{pr}(t) - T_{sg}(t)] \quad (8)$$

where, T_{pr} is coolant average temperature at steam generator, T_{hi} coolant temperature at steam generator inlet, T_{ho} coolant temperature at steam generator outlet, M_f is fuel mass, T_{sg} is steam temperature, and Γ is heat transfer capacity of steam generator.

2.2 Cold start up

For a faster and more efficient start-up for PWR-type SMR, the feasibility of an innovative cold nuclear start-up method is investigated. In this new method the external reactivity is wisely controlled to compensate thermal and xenon reactivity feedbacks and to slightly increase the reactor power until the core temperatures goes from room temperatures to HZP temperatures. After reaching HZP temperatures the reactor power is decreased to low power level (10 KW_{th}) for reactor physical tests, if the tests are passed, power of the reactor is increased to critical full power level.

For 300 MW_{th} small PWR, the following cold nuclear start up procedures are made:

1- The external reactivity is controlled to compensate thermal and xenon reactivity feedbacks and to increase the reactor power (in 30 minutes) from zero power to 3.9 MW_{th}, The reactor power is then remained constant at 3.9 MW_{th} (for 3 hours) until the core temperatures eventually reach HZP temperature (~559 °K).

2- After core temperatures reaches HZP temperature a negative reactivity insertion is introduced to decrease the reactor power (in 10 minutes) to 10KW_{th} for physical tests. In this simulation a 5 hours physical tests period is considered.

3- If the physical teats are passed, it means that the reactor is ready for full power start up. Therefore, the reactor power is increased from HZP to FHP (in 2 hours) by increasing the heat transfer capacity of steam generator (Γ), from 0% to 100% of its full power value, and by controlling the external reactivity. After that, the reactor power is kept at full power (with 100% Γ) for 24 hours.

The results of complete cold nuclear startup simulation procedures for reactor power, concentrations (of xenon and iodine), and reactivates (external reactivity, fuel reactivity feedback, coolant reactivity feedback, xenon reactivity feedback and total reactivity) are illustrated in figures 2, 5, 6, and 7 respectively. Fuel, clad and average core coolant temperatures during the cold nuclear startup are presented in fig. 3, while fig.4 illustrates core inlet and outlet coolant temperatures during the cold nuclear startup process.

The results are within the acceptable design ranges and demonstrate the feasibility of the proposed fast cold nuclear startup procedures.

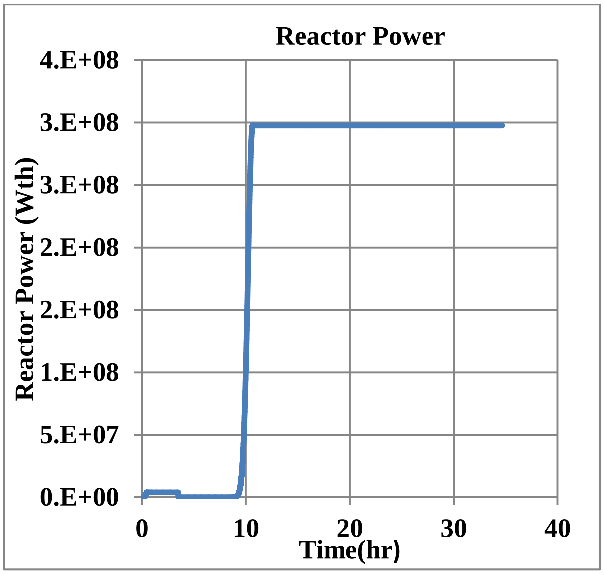

Fig. 2. Reactor Power during cold nuclear start up (all procedures)

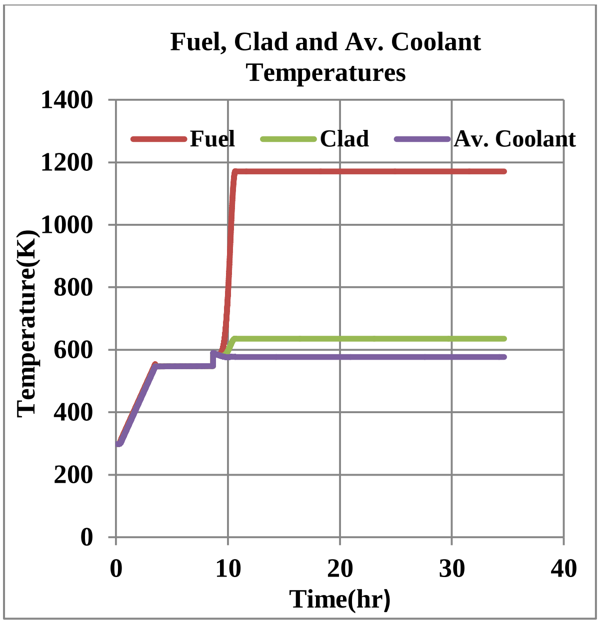

Fig. 3 Fuel, clad, and average core coolant temperatures during cold nuclear start up (all procedures)

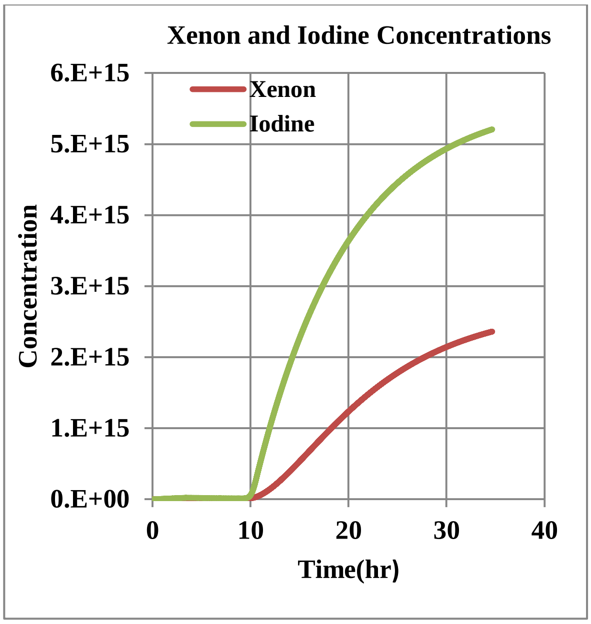

Fig. 5. Xenon and Iodine concentrations during cold nuclear start up (all procedures)

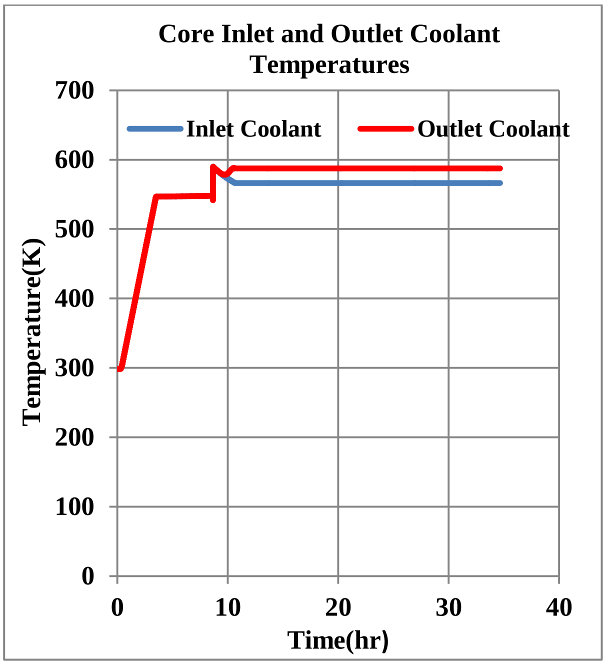

Fig. 4 Inlet and outlet core coolant temperatures during cold nuclear start up (all procedures)

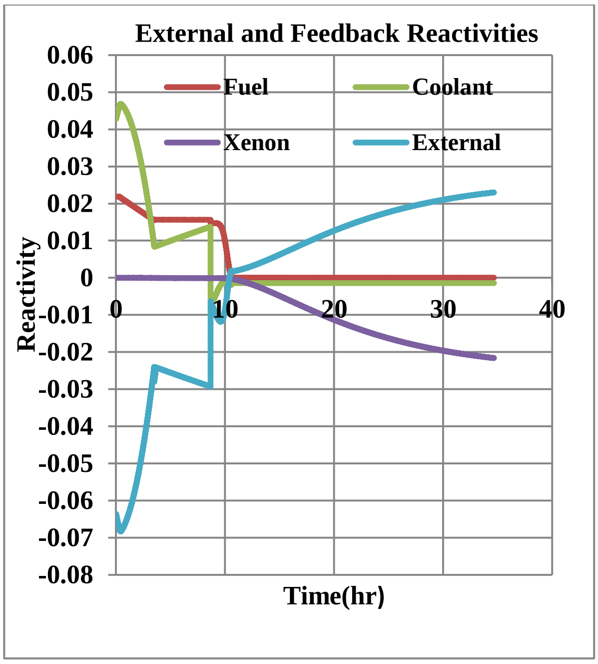

Fig. 6. External and feedback reactivates during cold nuclear start up (all procedures)

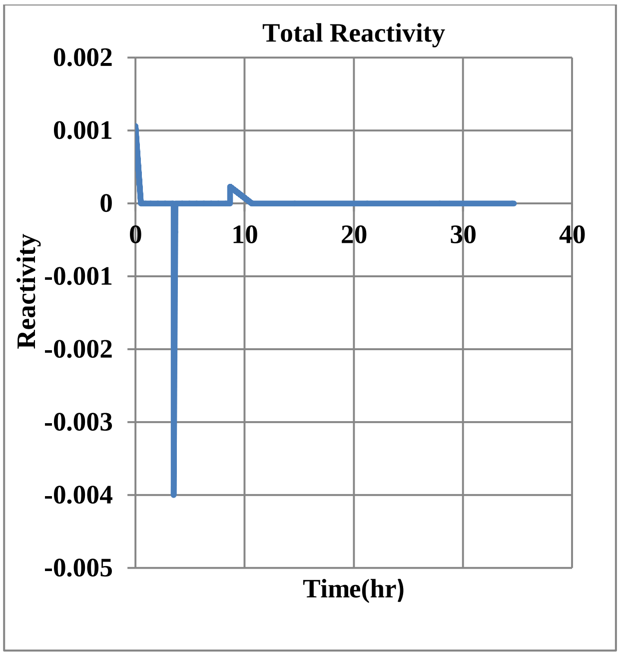

Fig. 7. Total reactivity during cold nuclear start up (all procedures)

3. Conclusion

The feasibility of cold nuclear start up for autonomous boron-free 300 MW_{th} small PWR is investigated. It is concluded that, cold nuclear startup is achieved using a three procedures method which permits raising the system temperatures from CZP values to HZP by controlling the external reactivity and heat transfer capacity of steam generator(Γ). The main cold nuclear start up periods are 3 hours at 3.9 MWth (to let the system temperatures go from CZP to HZP values), 5 hours at 10 KWth (to allow reactor physical tests), and 2 hours to increase the power level to FHP (if the physical tests are passed). The results demonstrate the feasibility of the proposed cold nuclear startup process.

The time of entire cold nuclear startup procedures for autonomous boron-free SMR, is only 640 minutes (10 hours and 40 minutes) which demonstrates a faster and more efficient cold start up method than the conventional method(which relies on the reactor pumping system).

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