Reactivity Coefficient Calculation for AP1000 Reactor Using the NODAL3 Code

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Abstract. The reactivity coefficient is a very important parameter for inherent safety and stability of nuclear reactors operation. To provide the safety analysis of the reactor, the calculation of changes in reactivity caused by temperature is necessary because it is related to the reactor operation. In this paper, the temperature reactivity coefficients of fuel and moderator of the AP1000 core are calculated, as well as the moderator density and boron concentration. All of these coefficients are calculated at the hot full power condition (HFP). All neutron diffusion constant as a function of temperature, water density and boron concentration were generated by the SRAC2006 code. The core calculations for determination of the reactivity coefficient parameter are done by using NODAL3 code. The calculation results show that the fuel temperature, moderator temperature and boron reactivity coefficients are in the range between -2.613 pcm/°C to -4.657pcm/°C, -1.00518 pcm/°C to 1.00649 pcm/°C and -9.11361 pcm/ppm to -8.0751 pcm/ppm, respectively. For the water density reactivity coefficients, the positive reactivity occurs at the water temperature less than 190 oC. The calculation results show that the reactivity coefficients are accurate because the results have a very good agreement with the design value.

Keywords: reactivity coefficient, inherent safety, NODAL3, SRAC2006, AP1000

1. Introduction
Westinghouse designed the advanced passive PWR (pressurized water reactor) reactor, AP1000 reactor, with a large electric power output of 1117 MW. AP1000 is designed with simple construction principles (simplicity) and modular to get cheap electrical charges, relatively [1]. The advantages of safety features of the AP1000 reactor have been evaluated in previous research works, such as criticality, peak power factor, reactivity, critical boron concentration time (critical boron concentration) and total outages reactivity (shutdown reactivity) [2-3].

The AP1000 designed has a better inherent safety since it has the negative total feedback reactivity coefficients. The negative reactivity coefficient ensures the reactor can stabilize the power when the reactor condition changes, such as fuel and moderator temperature increase when the power goes to the nominal level [4-7]. The fuel temperature coefficient (FTC) is reactivity change per fuel temperature change where the moderator temperature and density, as well as boron concentration, are maintained at constant condition. Another name applied to the FTC is the Doppler reactivity coefficient, often shortened to Doppler. Moderator temperature coefficient (MTC) is reactivity change...
per moderator temperature change where the fuel temperature, moderator density and boron concentration are maintained at a constant condition. The FTC is faster affects the power rise than the MTC because the fuel temperature immediately increases following a power increase, while the moderator temperature increase after several seconds.

This paper focuses on the evaluation of the FTC and MTC of the AP1000 for various water densities and boron concentrations because the temperature coefficient gives significantly to the inherent safety characteristics of the reactor. The MTC has been determined for the cold zero power (CZP) condition [8], however, the MTC for the hot and full power (HFP) condition is not carried out yet. Therefore, this paper shows the evaluation of the FTC and MTC for HFP condition. Besides the two main coefficient reactivities, the reactivity changes due to moderator densities and boron concentration are also carried out. The designed values of the AP1000 reactor are used as the references.

The reactivity coefficients are calculated by using the SRAC and the NODAL3 codes. The NODAL3 code solves steady-state as well as time dependent few-group nodal neutron diffusion equations in the 3-D Cartesian geometry and it is coupled with a simple thermal hydraulic model for typical PWRs. The verification has been conducted and their results showed that the NODAL3 code produces very satisfactory results for the steady-state and transient problems [9-11]. The SRAC code is used to generate the neutron diffusion group constants of fuel assemblies, control rod and reflector [12]. The core calculations using NODAL3 code are carried out to calculate the effective multiplication as a function of fuel and moderator temperatures, water densities and boron concentration.

2. AP1000 reactor core configuration

AP1000 reactor is a PWR reactor with two-loop which generates electrical energy of 1117 MW. The main design parameters for the AP1000 reactor resemble other PWR reactors. AP1000 reactor generates the thermal power of 3400 MW from 157 UO2 fuel assemblies with coolant and moderator are light water (H2O). The fuel has 3 uranium enrichments, 2.35%, 3.40% and 4.45%. Figure 1 shows the initial AP100 core configurations. Each of the AP1000 fuel assemblies comprises a 17 × 17 square lattice array of which 264 are fuel rods, 24 are guide tubes for reactor control and one central instrumentation tube.

![Figure 1. AP1000 core configuration [1]](image-url)
Figure 2 shows the different arrangements of the Pyrex and IFBA rods in the AP1000 fuel assemblies (FA). According to Fig. 2, the Pyrex and IFBA rods are arranged in FA with three and five different configurations, respectively. The number of Pyrex in the FA are 9, 12 and 24. The number of IFBA in FA with enrichment of 4.45% is 28, 44, 72, 88 and 112, except the FA with enrichment of 2.35 % only has 28 IFBA.

![AP1000 fuel assemblies configuration](image)

**Figure 2.** AP1000 fuel assemblies configuration [1]

### 3. Methodology

The NODAL3 code was used to calculate the criticality parameters, $k_{eff}$, by simulating the cores in the 3-D geometry of X-Y-Z model. All control rods were assumed to be fully up. The fuel and non-fuel zones of each standard and control fuel element were modeled separately. In the criticality calculation, some input data such as absorption macroscopic cross section ($\Sigma_a$), the fission macroscopic cross section ($\nu\Sigma_f$), the diffusion coefficient ($D$), the group scattering macroscopic cross section ($\Sigma_s, g\rightarrow g'$) and the fission spectrum for neutron energy groups, are needed in the NODAL3 code. The SRAC code was used for generating the diffusion group constants as a function of fuel temperatures and moderator temperatures as well as various boron concentration for all type of FA of
the AP1000 reactor. The HFP condition is set with the fuel temperature of 900 K, moderator and cladding temperatures of 600 K, based on the document of AP1000.

The number of nodes in the direction of X, Y, and Z is 17, 17 and 21, respectively. Based on the previous work of sensitivity analysis [13], the all core calculations are carried out with the 2 × 2 radial nodes per assembly, 1×18 axial layers per assembly, the maximum time step of 10 ms, and 9 and 1 ring divisions for fuel pellet and cladding [13]. The core configuration is made in ¼ full core model and the axial area is divided into 19 layers with a size of 20.3 cm (2 layers), 8.9 cm (2 layers), 24.553333 cm (15 layers). The upper and lower reflector has a thickness of 24.5. The AP1000 core layout model according to FA type for radial and axial direction are shown in Figure 3 and Figure 4, respectively.

**Figure 3.** AP1000 quarter-core layout assemblies with number of Pyrex (P) and IFBA (I)

**Figure 4.** Axial zone of a AP1000 fuel assembly
In the calculation of FTC, the moderator and cladding were taken as 600 K and the fuel temperature was varied. The cross-sections were generated using SRAC code by varying the fuel temperature from 573 K - 1273 K (300 °C – 1000 °C). Meanwhile to calculate the MTC by varying the moderator temperature from 373 K - 573 K (100 °C – 300 °C, temperature range at the normal operation), where the fuel temperature is 900 K and the cladding temperature is 600 K.

In the calculation of moderator density coefficients (MDC), the water density was varied from 0.965422 g/cm$^3$ (corresponding to 300 K) to 0.659757 g/cm$^3$ (corresponding to 600 K) where the fuel temperature is 900 K, as well as the moderator and cladding temperatures are 600 K. For the boron concentration coefficient (BCC), the concentration of boron in the moderator is varied in the range between 0 – 2500 ppm, (correspond to minimum and maximum boron concentration where the fuel temperature is 900 K and the moderator and cladding temperatures are 600 K, correspond to minimum and maximum boron concentration.

4. Results and discussions

Table 1 shows the accuracy of NODAL3 code (combination with SRAC2006 code) in the calculation of criticality parameters of the AP1000 reactor. The difference is about 0 % - 0.40% and the maximum difference occurs for full power without xenon condition. The NODAL3 calculation results showed a very good agreement with the designed value of the AP1000 reactor.

| Parameters | NODAL3 code | Reference (AP1000 design)[1] | Difference (%) |
|------------|-------------|-------------------------------|----------------|
| $k_{\text{nf}}$ (cold, clean, unborated water) | 1.330 | 1.330 | 0.00 |
| $k_{\text{eff}}$ (cold, zero power, boc, zero soluble boron) | 1.207 | 1.205 | -0.16 |
| $k_{\text{eff}}$ (full power, no xenon, hot RCCAs out, boron concentration 1184 ppm) | 0.996 | 1.000 | 0.40 |

The distribution of FTC for the without boron and with boron (1184 ppm) in the moderator are shown in Figure 5. It showed that the FTCs are negative for all fuel temperature range (300 °C – 1000 °C) with the values in the range between -4.66 pcm/°C to -2.61 pcm/°C. If we compare to the design values, the range of -6.3 pcm/°C to -1.80 pcm/°C which is obtained by the NODAL3 code, it lies in the range of the design value. Figure 5 shows that at the higher temperature gives the lower negative FTC. This trend is same as the reference of the AP1000 reactor.

![Figure 5. Fuel temperature coefficient for HFP condition](image-url)
The FTC for with and without boron will overlap at the fuel temperature higher than 900 °C. This is because of the Doppler effect for without boron will decrease significantly at the temperature higher than 600 °C. On the other hand, for the with boron condition, the effect of boron is strong enough to keep the gradient of FTC.

The calculation results of the MTC are shown in Figure 6, where all values are negatives, with the range of -3.62 to -3.61 pcm/°C and -1.006 to -1.005 pcm/°C for without boron and with boron, respectively. In comparison to the design value of the AP1000 reactor, 0 pcm/°C to -72 pcm/°C [6], the calculation results are in the range of design event through the range is more narrow. It is noted that the effect of fission products are dominant in the MTC. The higher boron concentration affects the MTC value is a trend to be positive especially at the low temperature. This is due to the reduction of boron concentration in the moderator produces a large increase in thermal utilization (f) when the moderator is heated up. This increased contribution is sufficient to change the sign of the overall moderator coefficient from negative to positive.

**Figure 6.** Moderator temperature coefficient for HFP condition

Before we discussed the MDC, it is understood when the temperature moderator increasing, moderator density decreases thereby increasing the possibility of leakage of neutrons and increase the probability of non-fission capture of these neutrons. Both effects cause a decrease in neutron population adding negative reactivity to the reactor core. Figure 7 shows the MDC results for the AP1000 reactor. It is found that MDC for the without and with boron (1184 ppm) are -18 pcm/g/cm$^3$ to 10 pcm/g/cm$^3$ and -21 pcm/g/cm$^3$ to 45 pcm/g/cm$^3$, respectively. It is clear that the higher boron concentration give more positive MDC value since in the higher boron concentration makes the moderator density decreases there for it produces the lower leakage of the neutron. The same situation is found in the design value of the AP1000 reactor. To avoid the positive MDC, the power is started when the moderator temperature reach 100 °C (moderator density 0.95 g/cm$^3$) by water flow friction and the boron is added slowly. The negative MDC is beginning to decline from the temperature of 190 °C (moderator density 0.9 g/cm$^3$).

Figure 8 summarizes the calculation results of BCC (boron concentration coefficient) are -9.11361 to -8.0751 pcm/ppm, while the design value are -13.5 to -5 pcm/ppm. The calculation results are still within the range of design value. The BCC show slight decrease trend with increase boron concentration. Boron concentration is decreased (diluted) to compensate the fuel depletion during one operational life cycle. The boron concentration (atoms/cm$^3$) decreases, resulting in a positive reactivity insertion and thermal utilization factor increases.
5. Conclusions

In this study, the characteristic of the AP1000 reactivity coefficients, such as fuel temperature (FTC), moderator temperature (MTC), moderator density (MDC) as well as boron concentration (BCC) have been evaluated by using NODAL3 code. All reactivity coefficients of the AP1000 reactor are negative, except the MDC at the lower temperature (\( < 190^\circ\)C) is positive. However, total reactivity coefficient is negative. This fact shows that the transient analysis should concern the MTC in the range between 20\(^\circ\)C – 190\(^\circ\)C.

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