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Pressurized nuclear plant ^{10}B abundance evolution study

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HIGHLIGHTS

- The evolution equation of ^{10}B abundance is deduced and verified by measurement.
- The equation is simplified by Taylor expansion without losing accuracy.
- The deviation between theoretical and measured boron concentration is well fixed.
- Useful measured data of ^{10}B abundance in some major systems is listed in detail.

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ABSTRACT

The boron concentration deviation between measurement and prediction in Pressurized Water Reactor (PWR) is mainly caused by the decrease of ^{10}B abundance. The evolution equation of ^{10}B abundance during the cycle is deduced according to theoretical calculation and also verified by measurement at different burn-up. The deviation between theoretical and measured boron concentration that frequently happened at long-cycle fuel reload management can be fixed with the equation.

1. Introduction

The phenomenon of large difference between theoretical and measured boron concentration (CB) has aroused people's interest and concern in PWR nuclear power plants over the past years. The difference has exceeded design criterion (50 ppm) for 11 times at MOL (middle of life) in Daya Bay nuclear power plant (with 2 units and 35 cycles till now). Although the deviation does not impact the safety criterion and the risk is normally under control, the related work, including analysis, day-to-day trend follow-up of CB, has to be done.

Some design software can not track the effect of ^{10}B, like SMART (Santamarina et al., 2004) developed by AREVA, or they do but with unsatisfactory accuracy, like ANC developed by Westinghouse (See ^{10}B adjusted by ANC code in Fig. 1). Besides, several studies (Asai et al., 1983; John and Neymotin, 1998; Guangming Cai, 2007) have been made to evaluate the ^{10}B depletion, but the method proposed in this article may be easier to use. Furthermore, the lack of detailed ^{10}B isotope analysis, coupled with the inaccurate data from the system, tend to make the correction incredible. While, in this article, the study of precise theoretical calculation and useful measured data of ^{10}B will be elaborated thoroughly.

2. Function of ^{10}B depletion

If there's no change to the coolant in the first loop, such as makeup or boration, the variation of the number of ^{10}B atoms is derived from their reaction with neutron:

$$\frac{dN_1}{dt} \approx -(\sigma_1\phi_1+\sigma_2\phi_2)N_1\frac{V_c}{V} = a_1N_1$$
$$a_1 \equiv -(\sigma_1\phi_1+\sigma_2\phi_2)\frac{V_c}{V} \qquad (1)$$

In above-listed equation, N_1 represents the number of ^{10}B,V_c and V, respectively, stand for the volume of core and the total volume of the RCP (Reactor Coolant System). σ_1, ϕ_1, σ_2, ϕ_2 are the cross section of ^{10}B and average flux in the core at full power for fast group and thermal group neutron in respective.

The cross sections could be assumed as constant and we only have to account the different neutron fluxes at BOL, MOL and EOL (BOL and EOL refer to begin of life and end of life. In fact, the neutron fluxes vary very slightly during the cycle).

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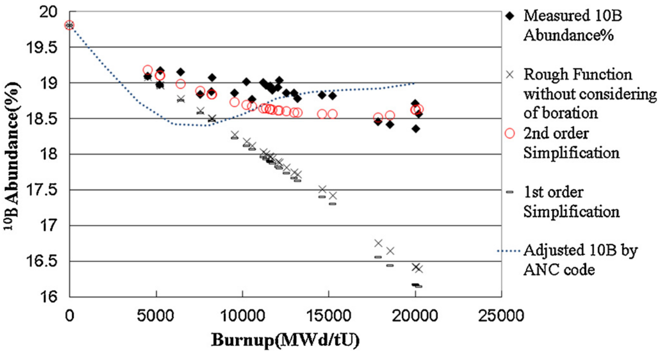

Fig. 1. ^{10}B abundance evolution during a typical 18 month cycle.

If dilution happens during T_1–T_2 (T represents time), the above equation has to be altered:

$$\frac{dN_1}{dt} = -(\sigma_1\phi_1 + \sigma_2\phi_2)N_1\frac{V_c}{V} - \frac{F_m}{V}N_1 = a_1N_1 + a_2N_1 \tag{2}$$

$$\frac{dN_2}{dt} = -\frac{F_m}{V}N_2 = a_2N_2 \tag{3}$$

N_2 represents the number of ^{11}B, F_m is the makeup water flowrate, $a_2 \equiv -F_m/V$.

The number density of ^{10}B and ^{11}B is deduced according to the above equation:

$$N_1(T_2) = N_1(0)\exp[a_1T_2 + a_2(T_2 - T_1)] \tag{4}$$

$$N_2(T_2) = N_2(0)\exp[a_2(T_2 - T_1)] \tag{5}$$

Therefore, the ^{10}B atom percent (a/o) as a function of time is given below:

$$x(T) = \frac{N_1}{N_1 + N_2} = \frac{1}{1 + N_2(0)/N_1(0)e^{-a_1T}} \tag{6}$$

If boration doesn't occur, the ^{10}B could drop from initial value 19.8% to 16.4% based on Eq. (6) for a 18-months cycle. But, the actual ^{10}B abundance is higher than that. If boration occurs between T_3 and T_4:

$$\frac{dN_1}{dt} = -(\sigma_1\phi_1 + \sigma_2\phi_2)N_1\frac{V_c}{V} + (F_b\rho_{REA}C_{REA}R_{REA})\frac{1}{m_{10}} - \frac{F_b}{V}N_1 = (a_1 + a_3)N_1 + b \tag{7}$$

$$\begin{aligned} \frac{dN_2}{dt} &= F_b\rho_{REA}C_{REA}(1 - R_{REA})\frac{1}{m_{11}} - \frac{F_b}{V}N_2 = a_3N_2 + c \\ a_3 &\equiv -\frac{F_b}{V}; \\ b &\equiv \frac{1}{m_{10}}F_b\rho_{REA}C_{REA}R_{REA} \\ c &\equiv \frac{1}{m_{11}}F_b\rho_{REA}C_{REA}(1 - R_{REA}) \end{aligned} \tag{8}$$

F_b is the flowrate of boration, which is assumed as a constant rate during T_3–T_4. ρ_{REA} is the density of boron acid in REA (Reactor Boron and Water Makeup System), C_{REA} is the concentration of boron *acid*, R_{REA} is the abundance of ^{10}B, and m is *related* to the atomic mass of boron.

So the number density of ^{10}B and ^{11}B accounting for boration at T_4 is:

$$N_1(T_4) = N_1(0)\exp[a_1T_4 + a_2(T_2 - T_1) + a_3(T_4 - T_3)] + \frac{b}{a_1 + a_3} \times \{\exp[(a_1 + a_3)(T_4 - T_3) - 1]\} \tag{9}$$

$$N_2(T_4) = N_2(0)\exp[a_2(T_2 - T_1) + a_3(T_4 - T_3)] + \frac{c}{a_3}\{\exp[a_3(T_4 - T_3)] - 1\} \tag{10}$$

at the moment T, The total number is:

$$N_1(T) = N_1(0)\exp\left[a_1T + \sum_i a_{2i}\Delta T_i + \sum_j a_{3j}\Delta T_j\right] + \frac{b}{a_1 + a_3}\left\{\exp\left[\sum_j (a_1 + a_{3j})\Delta T_j\right] - 1\right\} \tag{11}$$

$$N_2(T) = N_2(0)\exp\left[\sum_i a_{2i}\Delta T_i + \sum_j a_{3j}\Delta T_j\right] + \frac{c}{a_3}\left\{\exp\left[\sum_j a_{3j}\Delta T_j\right] - 1\right\} \tag{12}$$

ΔT_i is the duration of makeup time; ΔT_j is the duration of boration time. a_{2i} and a_{3j} represent the related coefficients defined above.

The relationship between the total makeup/boration volume and a_{2i}, a_{3j}, ΔT_i, ΔT_j is $\sum_i a_{2i}\Delta T_i = -V_m/V$, $\sum_j a_{3j}\Delta T_j = -V_b/V$, V_m and V_b are the makeup volume and boration volume, respectively.

Finally we can deduce the function of the ^{10}B atom percent (a/o):

$$x(T) = \frac{N_1(T)}{N_1(T) + N_2(T)} = \frac{1}{1 + N_2(0)/N_1(0)\varepsilon(T)\,e^{-a_1T}} \tag{13}$$

In the equation, the function $\varepsilon(T)$ represents the effect of boration compared to the original $x(T)$ function (6):

$$\varepsilon(T) \approx \frac{e^{(a2+a3)T} - k(e^{a3T} - 1)}{e^{(a2+a3)T} - k(e^{a3T} - 1)e^{(a4-a1)T}} \tag{14}$$

In this function, k stands for the concentrated ratio of boron acid in REA compared to RCP, which is calculated as follows:

$$k \equiv \frac{\rho_{REA}C_{REA}}{\rho C_0}$$

C_0 is the initial CB in RCP at BOL. a_4 represents the decrease coefficient of the abundance of ^{10}B in REA, as defined below:

$$a_4 \equiv \frac{1}{T}\ln\left(\frac{x_{REA}}{x_0}\right)$$

x_0 is the initial abundance in RCP at BOL. The expression of $x(T)$ is consistent with the original one while there is no boration. In the case of big amount of boration, that is, $V_b \gg V$, we get

$$\varepsilon(T) \approx \frac{e^{(a2+a3)T} - ke^{a3T}}{e^{(a2+a3)T} - ke^{(a3+a4-a1)T}}$$

$$x(T) = \frac{1}{1 + N_2(0)/N_1(0)\exp[-a_1T]\varepsilon(T)} \approx x_{REA}$$

It means the ^{10}B atom percent (a/o) would be close to that of the ratio in REA system while the plant experiences big amount of boration, which matches with the real situation.