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A Study on the boron depletion in 16x16 boron mixed fuel rods

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1. Introduction

The rare material such as gadolinium or erbium is widely used in nuclear power reactors which utilize longer cycle reload strategy. Recently study is initiated to use boron instead of rare material to reduce the dependency on the rare material amount. As an integrated burnable poison, Westinghouse has developed IFBA whose fuel pellet surface is coated with boron compound. Since each neutron absorption in boron-10 produces helium gas and it will increase internal pressure, in-depth study is required with respect to helium generation. In this paper approximate equation for boron-10 fraction is derived, and equation coefficients are proposed for the 16x16 fuel assembly for the fuel performance study.

2. Methods and Results

In this section boron-10 depletion is derived and an approximation is proposed.

2.1 Derivation of Boron-10 Depletion

Natural boron consists of about 20% of boron-10 whose neutron absorption cross section is large. Since a boron-10 captures a neutron, it will be divided into a Li-7 and an alpha particle. Therefore, boron-10 depletion follows the following simple relation:

$$\Delta N_b(t) = \sigma_b(t) N_b(t) \phi(t) \Delta t \qquad (1)$$

Where $N_b(t)$ is the boron-10 number density at time t, and $\phi(t)$, $\sigma_b(t)$ are neutron flux and the neutron capture cross section of boron-10, respectively. Then,

$$\frac{N(t)}{N(0)} = \exp(-\int_0^t \sigma_b(t')\phi(t')dt') \qquad (2)$$

By definition of burnup,

$$\begin{aligned} Bu(t) &= \int_0^t \kappa\Sigma_f(t')\phi(t')dt' \frac{V_{core}}{M_U} \\ &= \int_0^t P(t')dt' / M_U \end{aligned} \qquad (3)$$

From Eq. (3), neutron flux can be expressed as

$$\phi(t) = P(t)\cdot(V_{core}\cdot\kappa\Sigma_f(t))^{-1} \qquad (4)$$

Inserting Eq. (4) into Eq. (2), then

$$\frac{N_b(t)}{N_b(0)} = \exp\left(-\int_0^t \frac{\frac{P(t')}{V_{core}}\cdot\sigma_b(t')dt'}{\frac{\kappa\sigma_f\rho_U N_A}{M_{25}} w_{25}R(t') + I(t')} \right) \qquad (5)$$

Note that macroscopic fission cross section is initially of U-235 but some fissile plutonium isotopes contribute to the fission after depletion. In Eq. (5), σ_f is the microscopic U-235 fission cross section, ρ_U is the uranium density, N_A is the Avogadro constant, w_{25} is the U-235 enrichment, M_{25} is the U-235 isotope mass in amu. $R(t)$ and $I(t)$ are the U-235 number density decrease and fissile plutonium contribution at time t.

2.2 Simple Approximation

Since Eq. (5) contains time dependent characteristics in nuclides and microscopic cross sections, boron-10 content must be cycle dependent. However, the simplest form can be assumed and tested. If we neglect time dependency in the integral, Eq. (5) will have the following form:

$$\frac{N_b(Bu)}{N_b(0)} = \exp\left(-\frac{Bu}{a\cdot w_{25}+b}\right) \qquad (6)$$

The above equation is the same one used by IFBA design. For the 16x16 type fuel assembly, the two coefficients, a and b can be obtained by non-linear fitting from the depletion calculation.

2.3 Coefficient Determination

The DeCART[1] depletion calculations are performed to obtain the boron-10 density in the integrated poison rod as burnup increases. The numbers of boron bearing fuel(BBF) rods to be studied are chosen as 8, 44 and 84 to cover the effect of the burnable poison rods. Boron ppm of 500 and 1000 are considered for each 3 case. To find out the effect of the U-235 enrichment, three different enrichment set (3, 4, 5 w/o) is used.

Fig. 1 shows the calculation results for boron-10 depletion. As expected from Eq. (5) or Eq. (6), boron-10 fraction can be grouped by U-235 enrichment. The a and b are obtained such that $a = 1.4738$ and $b = 0.3194$, respectively.

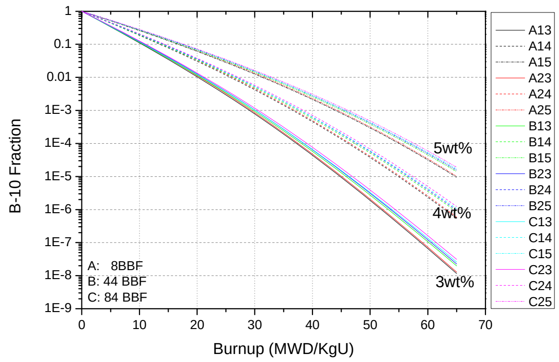

Fig.1. Boron-10 fraction vs. burnup

2.4 Proposed Approximation

Using the Eq. (6) with coefficients *a* and *b* above, boron-10 fraction is re-generated and compared with the DeCART calculation. Three typical cases are chosen for comparison. Fig. 2 shows that good agreement with the difference of 1.5% at 5 MWD/KgU burnup.

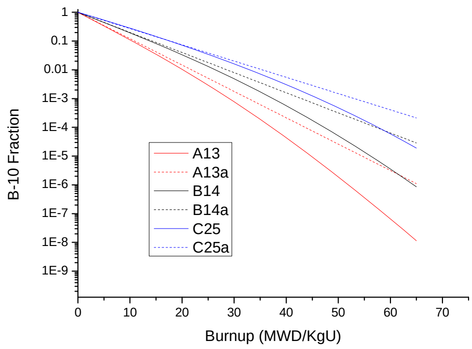

Fig. 2. Boron-10 fraction comparison between simple approximation and direct calculation

However, the relative error of the B-10 fraction becomes large as burnup increases. Since Eq. (5) has no approximation, it can be re-visited to find out the sources of error. Assume that R(t) and I(t) in Eq. (5) are linearly dependent on time t such that $R(t) = 1 - r \cdot t$ and $I(t) = q \cdot t$. Further assuming constant power *P*, and Eq. (5) can be re-arranged as:

$$\frac{N_b(t)}{N_b(0)} = \exp\left[\frac{-Bu}{cw - \frac{Bu \cdot M_u}{2P}(cwr - \frac{q(1-w)}{\sigma_b})}\right] \qquad (7)$$

where $c = \dfrac{N_A \kappa \sigma_f}{M_{25}\sigma_b}$.

Therefore as burnup increases, denominator becomes smaller than that of Eq. (6) because uranium reduction is faster than plutonium production as shown in Eq. (7). Therefore, the form of Eq. (7) is used to develop a proposed approximation as follows:

$$\frac{N_b(t)}{N_b(0)} = \exp\left(\frac{-Bu}{aw_{25} + (bw_{25} + c)Bu}\right) \qquad (8)$$

Where a=1.59389, b= -0.00773 and c=0.01051. In Fig. 3, proposed approximation is again compared with the direct calculations. The large relative approximation error after 30 MWD/kgU is because of inadequate representation of U-235 and fissile Pu. However, better agreement can be found in Fig. 3 than in Fig. 2 due to the consideration of burnup dependency of U-235 and fissile Pu by simple linear approximation.

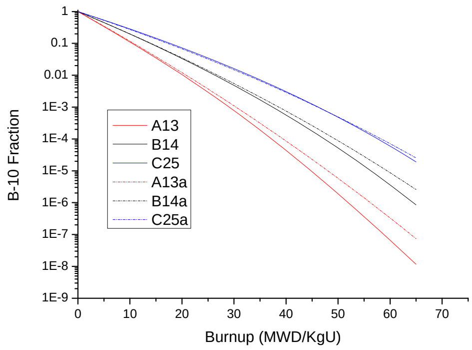

Fig. 3. Boron-10 fraction comparison between proposed approximation and direct calculation

3. Conclusions

Boron-10 depletion is simulated for the 16x16 fuel assemblies with boron mixed fuel rods using DeCART code. From the sensitivity calculations and physical form of the boron depletion in a fuel rod, an approximation is proposed for the performance analysis of the boron mixed fuel rod. The proposed approximation gives maximum 1.0% difference.

REFERENCES

[1] Jin Young Cho, et. al., KAERI/TR-3438/2007, DeCART V1.2 User’s Manual, Korea Atomic Energy Research Institute, 2007.7.