Implementation and Verification of Quadratic Depletion Method in Direct Whole Core Calculation Code nTRACER

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1. Introduction

Accurate treatment of gadolinium (Gd) depletion is one of the major issues in developing a reactor analysis code. Because of the large thermal absorption cross-sections of Gd-155 and Gd-177, the depletion of gadolinium isotopes leads to a significant change in the flux distribution. The first approach to properly mitigate the strong influence of Gd in depletion calculations is to use small depletion time steps. However, this approach is not desirable particularly in direct whole core depletion calculations that require excessively long computing time. A better approach is to use a more elaborated depletion method. In this regard, a quadratic depletion method incorporating the post correction method[1] have been proposed and proved to effective by the CASMO5 calculations. The whole core transport code developed at Seoul National University, nTRACER[2], adopts the quadratic depletion and post correction method and the Krylov depletion method[3] in order to perform accurate depletion calculations for power reactors involving considerable Gd loading with sufficiently large depletion time step sizes. In this paper, the implementation of the quadratic depletion method is presented and the effectiveness of the method and the accuracy of nTRACER depletion are demonstrated with the applications to the YGN3 and UNC5 initial core depletion analyses.

2. Quadratic Depletion with Post Correction

In the conventional semi Predictor-Corrector (P-C) method, the absorption reaction rate is assumed to be constant during the depletion time step. Thus sufficiently small time step sizes are needed to make this assumption valid. For Gd bearing assemblies, about 4 times smaller time step sizes than those of unshimmed fuel assemblies are needed. In order to employ relatively large depletion time step sizes while retaining the solution accuracy, the variation of the reaction rate should be considered. The quadratic depletion method is to approximate the reaction rate of the Gd isotopes with a quadratic polynomial. Then, the large variation of the absorption rates can be mitigated better in the depletion calculation. The post correction method allows avoiding the additional flux calculation needed after the second depletion calculation for Gd depletion. In the following subsections, the quadratic depletion method and post correction method are detailed.

2.1 Quadratic Depletion Method

In the quadratic depletion method, the microscopic absorption rate of the Gd isotopes is expressed as a quadratic polynomial of the Gd-155 number density. Specifically, the reaction rate of the *i*-th Gd isotope is expressed as follow:

$$R_i(t) = \sigma_i(t)\phi(t) = a_i \Delta N(t)^2 + b_i \Delta N(t) + c_i \qquad (1)$$

where a_i , b_i and c_i are the coefficients for the *i*-th isotope and $\Delta N(t)$ is the Gd-155 number density difference between time t and t_n . Because Gd-155 shows the most drastic number density change among the Gd isotopes during depletion, its number density is selected as the functionalization parameter. The coefficient at the time step between t_n and t_{n+1} can be determined by using the reaction rate information at t_{n-1} , t_n and t_{n+1} of the predictor step. Therefore, the quadratic depletion method is applicable only to the corrector step.

2.2 Post Correction Method

In the conventional semi P-C method, the flux calculation of corrector step is omitted in order to save computational time. However, the second flux calculation need to be done in the case of a Gd bearing assembly in order to obtain an accurate flux for the subsequent time step. However, if the number densities of the predictor step are improved, the flux solution at the predictor step would be accurate enough to skip the second flux calculation. The accuracy improvement of number densities at the predictor step can be made by employing the post correction which assumes the following exponential variations of the number densities:

$$N^p_{n+1} = N^c_n \exp[-R^p_{n+1}\Delta t]$$
$$N^c_{n+1} = N^c_n \exp[-R^c_{n+1}\Delta t] \qquad (2)$$

From the known the predictor number density at the predictor step (N^p_{n+1}), the predictor reaction rate (R^p_{n+1}) can be determined and then the corrector reaction rate (R^c_{n+1}) can be determined under the assumption that the ratio of these two at the current step is the same as that of the previous step. Namely,

$$f_{n+1} = \frac{R^c_{n+1}}{R^p_{n+1}} = \frac{\ln(N^c_{n+1}/N^c_n)}{\ln(N^p_{n+1}/N^c_n)} \cong f_n \qquad (3)$$

This leads to the following post correction number density with which the new flux calculation is to be performed:

$$N^{pc}_{n+1} = N^c_n \exp[\ln(N^p_{n+1}/N^c_n) f_n] \qquad (5)$$

The correction factor is updated as:

$$f_n = f_{n-1} \ln(N_n^c / N_{n-1}^c) / \ln(N_n^p / N_{n-1}^c) \quad (6)$$

3. Verification of Effectiveness

In order to examine the performance of the quadratic depletion model with post correction, nTRACER was applied to OPR1000 assembly depletion problems and the depletion calculation of the initial cores of YGN3 and UCN5 which have considerable loading of 4% and 6% Gd, respectively.

3.1 OPR 1000 Assembly Depletion Calculations

The depletion calculation the C1 assembly (8 rods of 4% Gd) of YGN3 and the B1 assembly(8 rods of 6% Gd) of UCN5. The k-inf behavior is shown as a function of burnup in Figs. 1 and 2. It is noted that the results obtained with the new method agree well with the references whereas large errors greater than ~1% are observed near the peak k-inf for the conventional depletion method (Semi P-C).

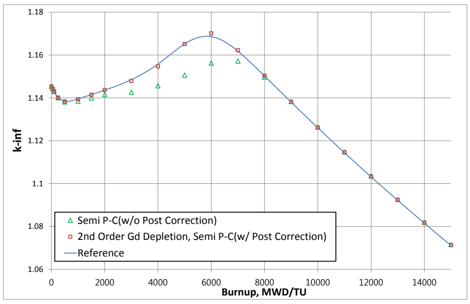

Fig. 1. k-inf vs. Burnup for C1 Assembly of YGN3C1

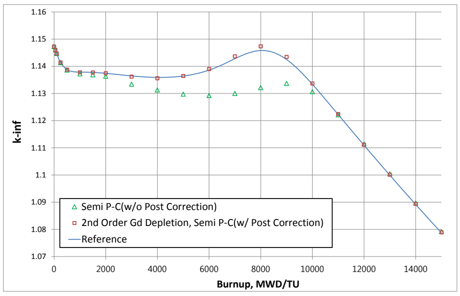

Fig. 2. k-inf vs. Burnup for B1 Assembly of UCN5C1

3.2 OPR 1000 Core Deletion Calculation

As shown in Figs. 3 and 4 that compare the calculated critical boron concentrations (CBC) with the measured values, the agreement with the measurement is good for YGN3 whereas it appears somewhat bad for UCN5 in the middle of cycle. At first glance it appears that the difference is due to the misprediction of Gd depletion for the core with higher Gd concentration. However, it turned out that this discrepancy resulted from the B-10 depletion problem[4]. Note that B-10 in the primary loops is reduced roughly by 1% per GWD/T so that the B-10 abundance at the burnup of 6GWD/T is about 6% less than that of fresh boron leading to an increase of about 36ppm in the measured CBC of ~600 ppm. The B-10 depletion problem was, however, not noticed in the YGN3 initial core. It was confirmed from the reactor operation history that frequent boration was made for various tests for YGN3C1 which was the first OPR1000 in Korea so that B-10 depletion had little impact.

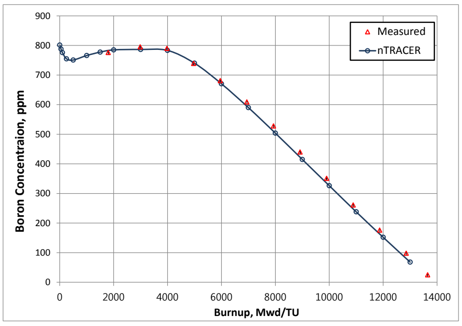

Fig. 3. CBC vs. Cycle Burnup for YGN3C1

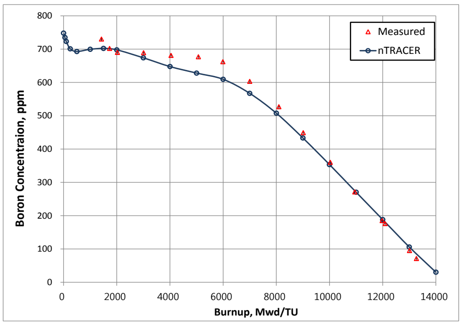

Fig. 4. CBC vs. Cycle Burnup for UCN5C1

4. Conclusions

The quadratic depletion method with post correction was implemented successfully in the directly whole core transport code nTRACER. As a consequence, the rapid depletion of the Gd isotopes could be proper mitigated with sufficiently large time step sizes as confirmed by the depletion results for the OPR1000 Gd bearing assemblies and two initial cores involving substantial Gd loading. It was also verified that the B-10 depletion effect turned out to be important for a reactor operating continuously with rare shutdown.

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