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CASMO-5 VERSUS MCNP-5 BENCHMARK OF RADIAL POWER PROFILE IN A FUEL PIN

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ABSTRACT

The radial power profile in a fuel pin is an important piece of information for transient analysis. Based on single fuel region assumption in the U-238 resonance treatment, CASMO-5 relies on an empirical radial distribution function for the U-238 resonance integral. The burnup-dependent radial power profile in a typical UO_2 fuel pin is examined as a numerical benchmark between CASMO-5 and MCNP-5 depletions. As a result, a new set of fitting parameters for the distribution function is found for CASMO-5 to better match the MCNP-5 results at high burnups. Running CASMO-5 with new fitting parameters verifies the improvements in agreeing with the burnup-dependent MCNP-5 radial power results. However, except the local power profile, there are no noticeable reactivity effects during depletion. The total amount of plutonium production in the fuel is also independent of the U-238 resonance integral distribution function.

Key Words: Radial power profile, U-238 resonance integral, depletion

1. INTRODUCTION

The radial power distribution in a fuel pin is an important piece of information for analyzing various transient scenarios. The fuel pellet needs to be spatially sub-divided into several concentric rings for the purpose of computing the radial power profile. There are recent discussions on development of spatially dependent resonance self-shielding method (SDDM) [1] to directly generate multi-region effective cross sections for resonance nuclides. In contrast, the current Studsvik lattice physics code, CASMO-5, is based on single fuel region assumption in the resonance treatment. Therefore, an empirical radial distribution function for the U-238 resonance integral is used when there are multiple ring sub-divisions requested by the user for the fuel pellet.

This paper is to benchmark the CASMO-5 burnup-dependent radial power profile against the reference MCNP-5 (coupled with ORIGEN-2) depletion results for a typical UO_2 fuel pin. The discrepancies between the two codes provide insightful suggestions in improving CASMO-5's default U-238 resonance integral radial distribution fitting parameters, and help us to understand the detailed physics in a fuel pin depletion problem. In addition, the traditional single fuel region assumption for depletion is tested, and proved to be an excellent approximation. Note that, in the production analysis, the fuel pellet is not sub-divided except the gadolinium-poisoned fuel (to account for the strong gadolinium self shielding due to its huge thermal cross sections).

2. CODE MODELS

2.1. CASMO-5

CASMO-5 [2] is a multi-group two-dimensional transport theory code for burnup calculations on LWR assemblies or simple pin cells. It is used in this paper for a pin cell burnup calculation to investigate the burnup-dependent radial power profile within the pellet. Note that, for UO_2 fuel without gadolinium, there is only one fuel region by default for the production analysis. For our purpose, one thus needs to specify multiple ring sub-divisions in the fuel pellet. Furthermore, the U-238 resonance treatment still assumes the fuel pellet as a single region. An exponential-form radial distribution function [3] in the fuel pellet for the U-238 resonance integral is used as:

$$f(r) = a_0 + a_1 e^{a_2 (R-r)^{a_3}} \tag{1}$$

where R is the outer radius of the fuel pellet. The default fitting parameters ($a_0 = 1, a_1 = 3, a_2 = -9.7, a_3 = 0.5$) are taken from Ref. [3], and will be referred to as the DRI parameters from here on. This distribution is imposed only on the effective U-238 absorption cross sections in the resonance energy groups. The weighting factor, w_i, for each radial ring i is computed as:

$$w_i = \int_{r_{i-1}}^{r_i} f(r) r dr \Big/ \int_{r_{i-1}}^{r_i} r dr \tag{2}$$

These weighting factors are then applied to modify the effective U-238 absorption cross sections in resonance groups as

$$\sigma_{a,i} = w_i \sigma_a \tag{3}$$

The normalization condition is such that

$$\sum_i N_i V_i \sigma_{a,i} = \sum_i N_i V_i \sigma_a \tag{4}$$

where N_i is the U-238 number density in the radial ring i and V_i is the local volume. Assuming a constant group flux across the fuel pellet, the normalization condition implies that the total resonance U-238 absorptions are preserved.

2.2. MCNP-5 Depletions

MCNP-5 [4] is a generalized geometry, continuous energy Monte Carlo transport code. It can provide a neutronic solution for the given configuration. As a one-group depletion and radioactive decay code, ORIGEN-2 [5] can be used to perform depletions using the MCNP-calculated fluxes and reaction rates. These two codes are coupled together to do burnup calculations using the linkage code, MCODE-2.2 [6], which implements a predictor-corrector approach for burnup calculations similar to that used in CASMO-5.

The neutron cross section libraries for MCNP-5 are point-wise, continuous-energy, which are processed consistently using NJOY99 with same tolerance parameters as the CASMO-5 586-group data library. Both libraries are based on the same nuclear data, ENDF/B-VII.0 [7]. In addition, the nuclear decay data and fission product yield data are updated in ORIGEN-2 libraries for depletion calculations.

A simple 3-D pin cell model is created in MCNP-5, where the top and bottom surfaces are reflective boundaries in order to mimic the 2-D CASMO-5 pin cell case. The depletion steps are also same as CASMO-5 values. The number of neutron histories for each MCNP-5 point is four million, i.e., 450 cycles (first 50 as inactive cycles) and 10000 source neutrons per cycle.

3. TYPICAL UO_2 PIN CELL CALCULATION

A typical 4.1-w/o-enriched PWR UO_2 pin cell case, taken from Ref. [1], is examined. The fuel pellet is divided into 17 concentric radial rings: for inner 9 rings each has a volume fraction of 0.1, and for outer 8 rings each has a volume fraction of 0.0125. The depletion is performed at hot full power conditions. Figure 1 shows the CASMO-5 vs. MCNP-5 comparison of radial fission rate distributions at BOL and 60 MWd/kg. At BOL, a satisfactory agreement is observed. However, at 60 MWd/kg, CASMO-5 clearly underestimates the fission rate in outer fuel rings.

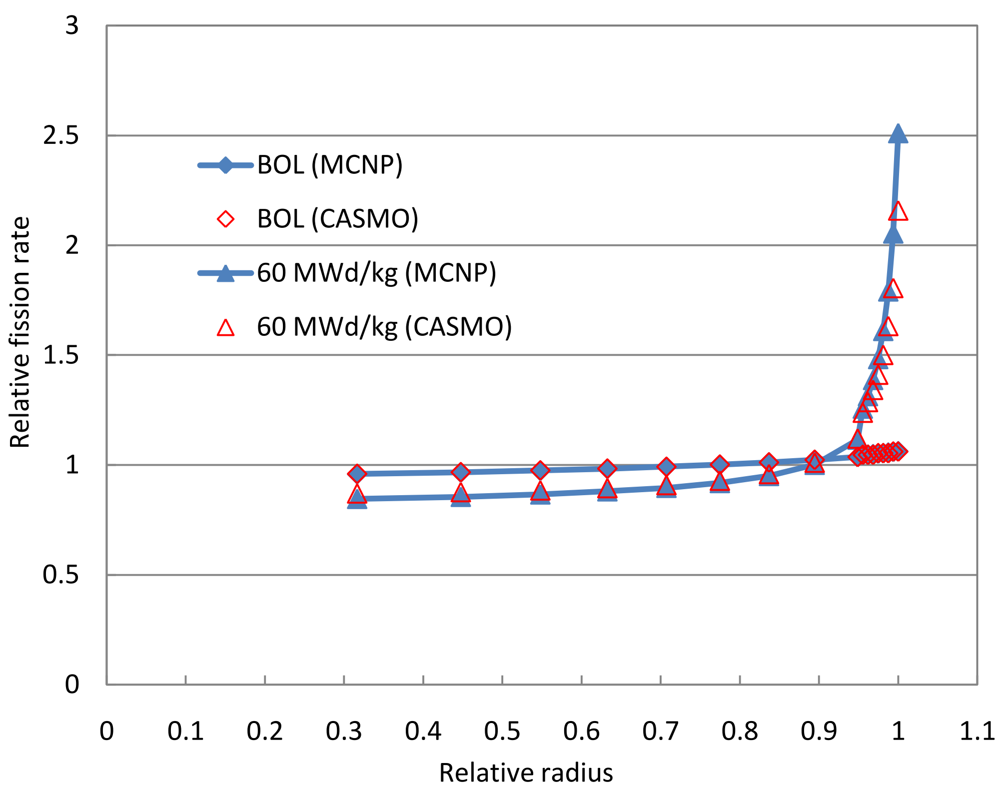

Figure 1. Fission rate comparison between CASMO-5 and MCNP-5.

It is well known that the sharp peak of fission rate distribution at high burnups is so called RIM effect. Due to the spatial resonance self-shielding, there are more U-238 absorptions in the outer rings. More plutonium, therefore, is produced towards the surface of the fuel pellet that leads to the sharp peak of the fission rate distribution. This phenomenon becomes more predominant as burnup increases. Thus, the discrepancy between CASMO-5 and MCNP-5 at high burnups indicates potential errors of the DRI parameters in CASMO-5. Note that one important update of CASMO-5 over older versions of CASMO-4 is to expand the data library from 70 groups to 586 groups. First few resonance groups in the 70-group structure are now fully resolved into very fine energy groups, and are not accounted as resonance groups any more. This change in resonance groups might suggest an update for the DRI parameters.

The U-238 absorption rate is examined at BOL. As shown in Fig. 2, the CASMO-5 U-238 absorptions are lower in outer rings based on the current default DRI parameters. It is, however, possible to find a new set of DRI parameters for CASMO-5 to match the MCNP-5 profile. With a trial-and-error approach, such a new set of DRI parameters is identified as: $a_0 = 1, a_1 = 5, a_2 = -13.0, a_3 = 0.5$, which shows sizable improvements in agreeing with the reference MCNP-5 results. One side note is that the U-238 absorption distribution is insensitive to the nuclear data sources, i.e., both ENDF/B-VII.0 (E7R0) and ENDF/B-VI.8 (E6R8) give the same U-238 absorption profile.

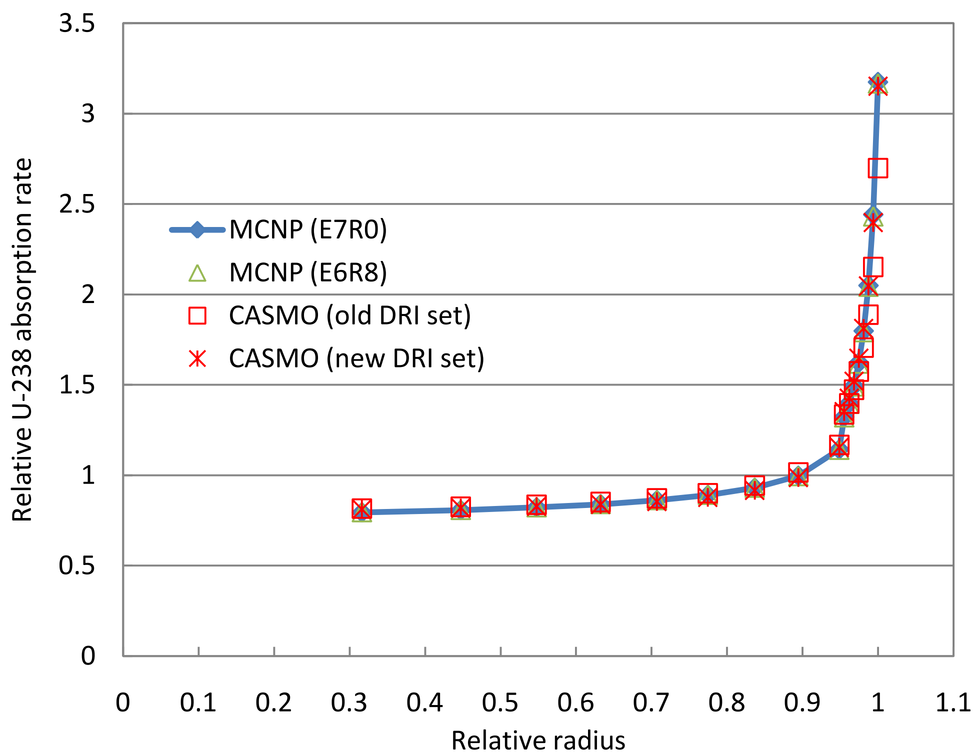

Figure 2. U-238 absorption rate distribution at BOL.

With the new set of optimized DRI parameters, the CASMO-5 pin cell depletion is re-performed. As expected, Figure 3 verifies the improved fission rate profile agreement between CASMO-5 with new set of DRI parameters and MCNP-5 results.

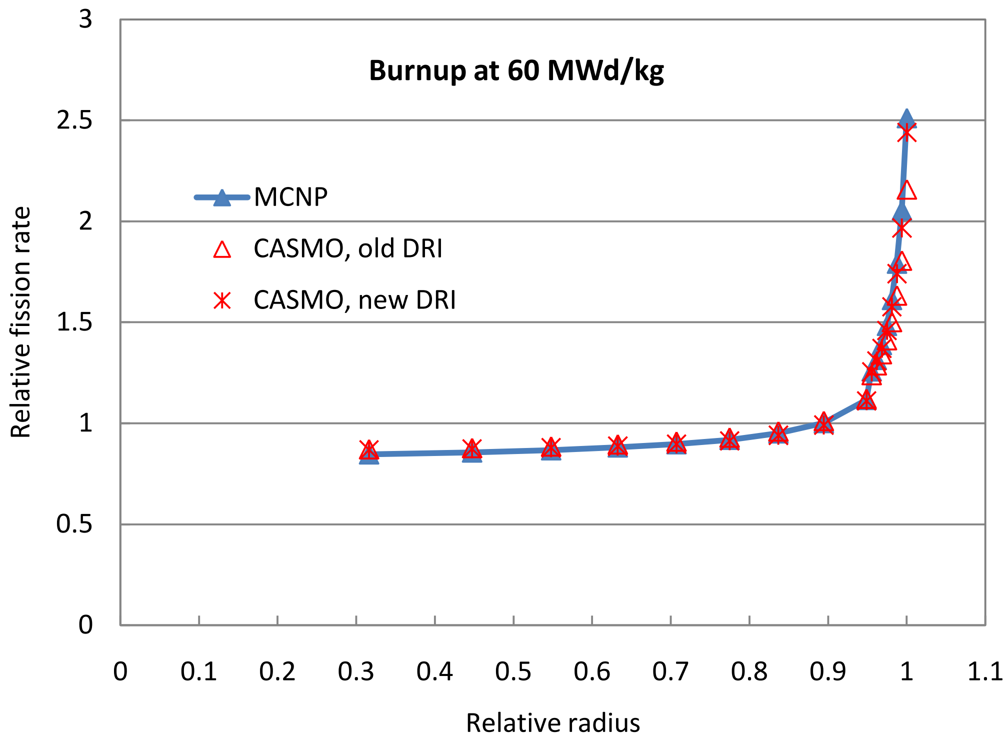

Figure 3. Fission rate comparison at 60 MWd/kg.

In CASMO-5 production analysis, by default, all gadolinium-free UO_2 fuel pellets have no radial sub-divisions for burnup calculations. The traditional single-region approximation ignores the spatial details inside the fuel pellet and is usually deemed adequate for LWR analysis. As a verification, this assumption is investigated in parallel by CASMO-5 and MCNP-5 depletions. For the same UO_2 pin cell problem, single-region depletions are performed by CASMO-5 and MCNP-5/ORIGEN-2. In this case, the DRI model in CASMO-5 should be irrelevant. The single-region depletion results are then compared to the 17-ring depletion results. Figs. 4 and 5 show the CASMO-5 results, and Figs. 6 and 7 show the MCNP-5 depletion results. The oscillations of eigenvalue differences in Fig. 6 indicate the unique feature of Monte Carlo statistical fluctuations. Both codes give the same answer, i.e., the traditional single-region approximation holds so well that there is neither a noticeable reactivity impact nor a plutonium difference. From a neutron balance point of view, the difference of the detailed plutonium profiles in the fuel pellet is minimal. The plutonium fission and absorption rates are same as long as the total amount is the same. Furthermore, when looking at the current LWRs, the U-238 number density changes only slightly during depletion, which ensures the validity of imposing a constant U-238 resonance integral (RI) distribution function.

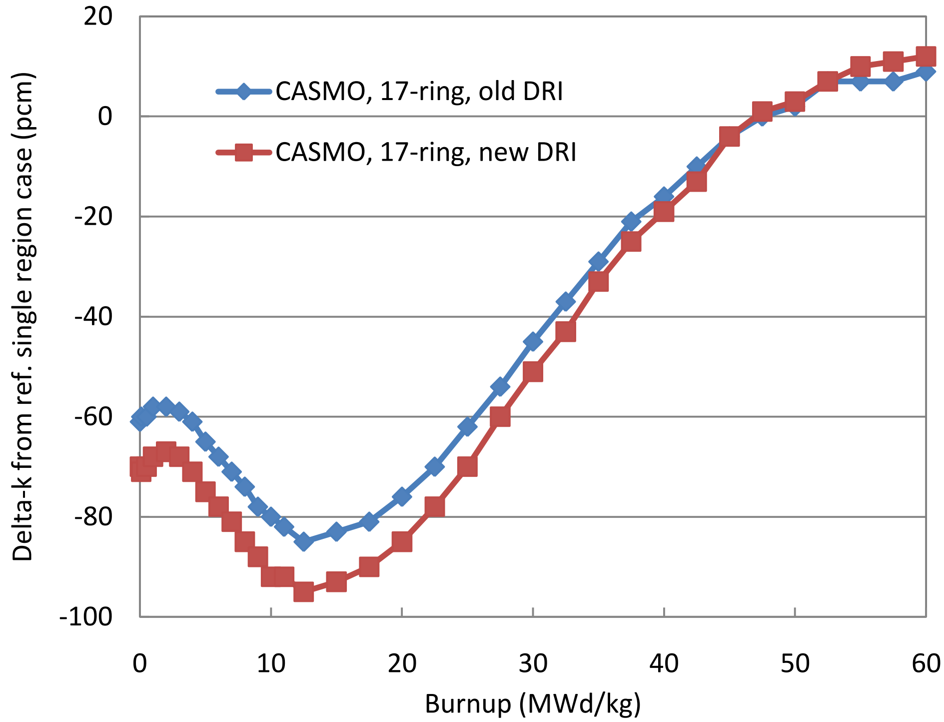

Figure 4. Eigenvalue impact of one region approximation by CASMO-5.

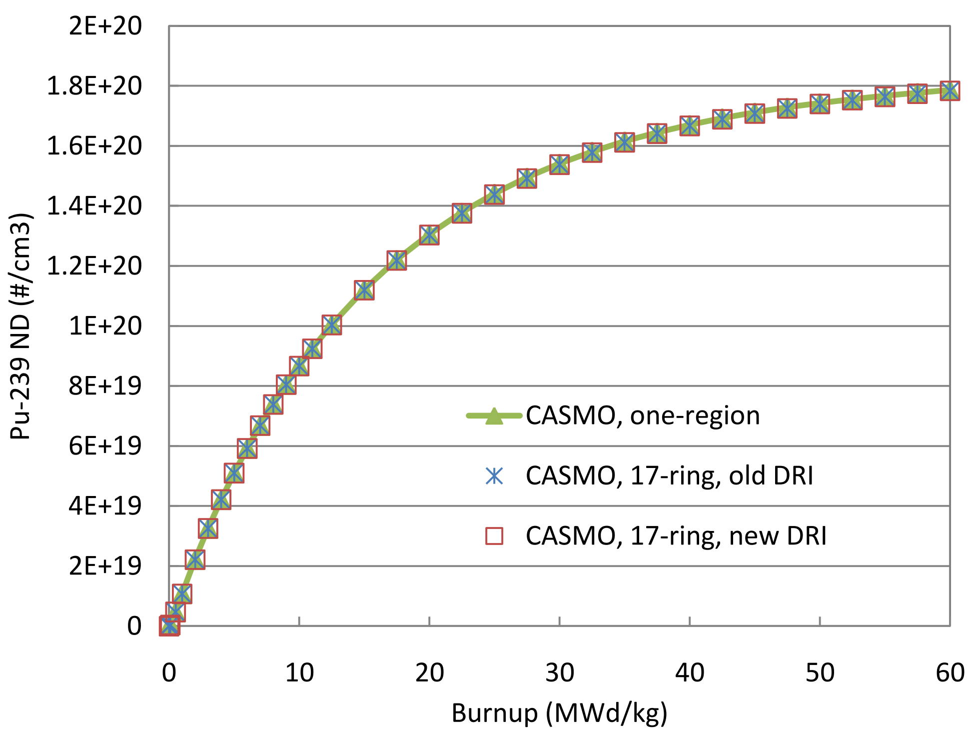

Figure 5. Pu-239 average number densities in the fuel by CASMO-5.

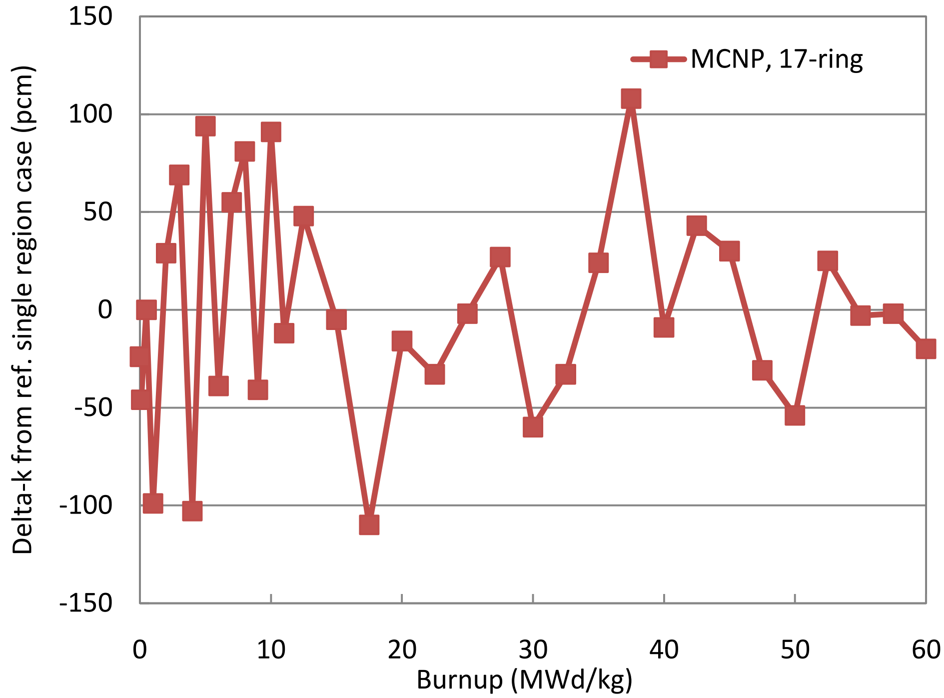

Figure 6. Eigenvalue impact of one region approximation by MCNP-5 depletions.

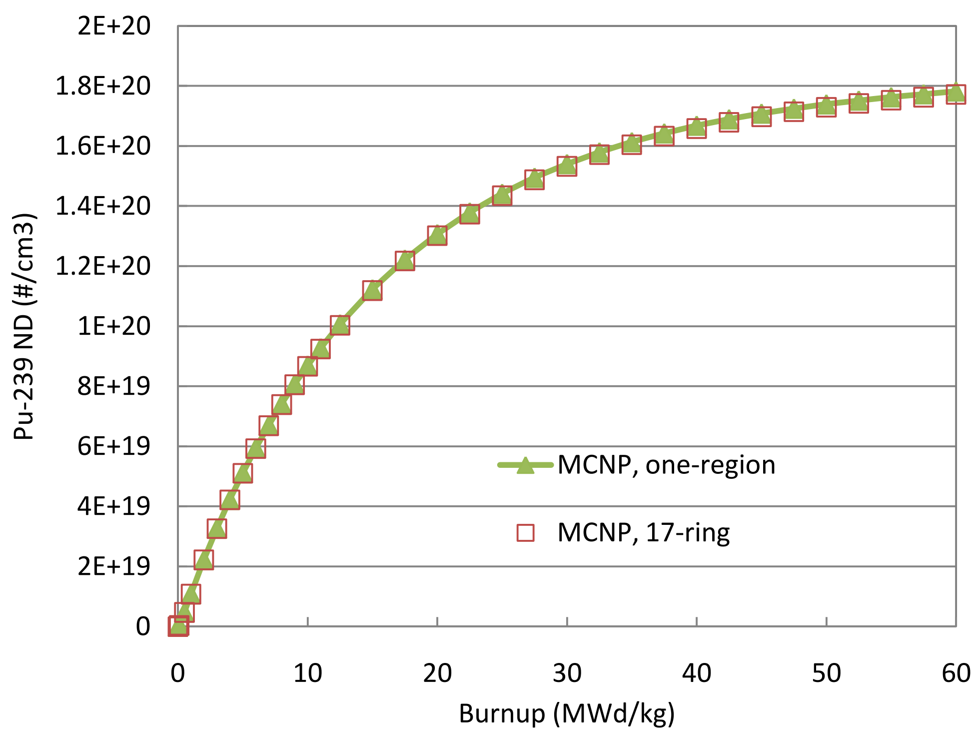

Figure 7. Pu-239 average number densities in the fuel by MCNP-5 depletions.

The UO_2 pin cell examined here represents a typical PWR lattice. Several other pin diameters, particular BWR rods, have been investigated showing similar results. As a matter of fact, if expressed in units of relative radius, the burnup-dependent relative fission rate profile is very similar between a PWR UO_2 fuel rod and a BWR UO_2 fuel rod.

4. CONCLUSION

The radial power profile in a fuel pin is examined by CASMO-5 and MCNP-5 depletions in this paper. Several major conclusions are:

- The CASMO-5 fission rate distribution calculation is very accurate. However, potential errors can occur during depletion due to improper plutonium distribution in the fuel pellet from the old DRI parameters.

- By matching the reference MCNP-5 depletion results, a new set of DRI parameters ($a_0 = 1, a_1 = 5, a_2 = -13.0, a_3 = 0.5$) is found for CASMO-5, which improves the fission rate distribution at high burnups.

- The traditional single-region approximation holds very well for typical UO_2 fuel rods. Even though the detailed spatial information in the fuel pellet is ignored, the pellet-averaged number densities agree well with the multi-region pin cell calculations. No noticeable reactivity effect is found.

Note that, for all calculations reported in this paper, a constant radial fuel temperature profile is assumed. A realistic fuel temperature profile, e.g., classic parabolic distribution, will flatten the fission rate distribution somewhat in the fuel rod.

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