Preliminary study of cobalt emitter's depletion effects using STREAM/RAST-K

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1. Introduction

In domestic pressurized water reactors, existing core monitoring systems (CMS) based on rhodium-based self-powered neutron detectors (SPND) can provide flux distribution data. From this feature, the in-core instrument assembly (ICI) has been designed to use for core monitoring system to measure spatial distribution of in-core flux within normal operation. However, the application of rhodium-based ICIs to core protection systems is limited, since rhodium SPND signals are governed by delayed responses. In contrast, cobalt emitters generate prompt signals, with current amplitudes directly proportional to the (n,γ,e) reaction of emitter nuclides. With the compact design of small modular reactors (SMRs), the necessity to eliminate ex-core detectors and integrate core protection functions into ICIs has become increasingly important.

However, it is known challenge that the neutron-absorbed cobalt-60, from burned emitter has half-life as 5.26 years, generates the additional current from spontaneous beta decay within whole designed fuel cycle [1]. This is the main cause of depletion effect of cobalt SPND. In this paper, for the preliminary study, the procedures of depletion of cobalt SPND are introduced.

Cobalt emitter in SPND has been explicitly modelled for precise resonance treatment and corresponding depletion calculation of emitter nuclides. The group constants for detector signal calculation have been produced within the fuel assembly lattice calculation as the pre-defined case matrix using STREAM [2]. The absorption reaction rates of SPNDs over 61 ICI and 3-axial positions have been calculated during the whole-core depletion using RAST-K [3].

The ultimate objective of the cobalt emitter study is to investigate photoelectric effects, gamma-ray interactions, and rod shadowing effects in boron-free SMRs. As a preliminary step, the explicit neutronics behavior was first examined under the condition that ICIs are actually installed in an APR1400 reactor.

2. Methods & Results

2.1. Cobalt SPND signal

The STREAM/RAST-K provides in-core detector signal calculation module for the three-dimensional whole-core calculation. STREAM implements group condensed constants of reaction of the emitter, for given case matrix and burn-up condition. RAST-K utilizes those group constants to calculate neutron absorption reaction rates in position (r, z),

$$RR(r,z) = N_{det} \sum_{g} \sigma_g^{det} \alpha_g^{det} \phi_g^{FA}(r,z) \quad (1)$$

where N_{det} is the number density, and σ_g^{det} is effective absorption cross-section (XS) of emitter nuclides. α_g^{det} is the pre-calculated flux ratio of emitter region and fuel assembly, also known as box-to-pin factor, and ϕ_g^{FA} is the assembly-wise averaged nodal flux [4].

2.2. Instrumented fuel assemblies

2.2.1. Explicit modeling of ICI

The explicit modeling of ICI thimble is shown in Figure 1. The sub-figure of right-above shows the original implementation of ICI modeling. In fact, there was no actual material in instrumentation tube (IT), assuming that the emitter's burnup effect is negligible and the resonance treatment is enough for using the table of resonance integrals (RI).

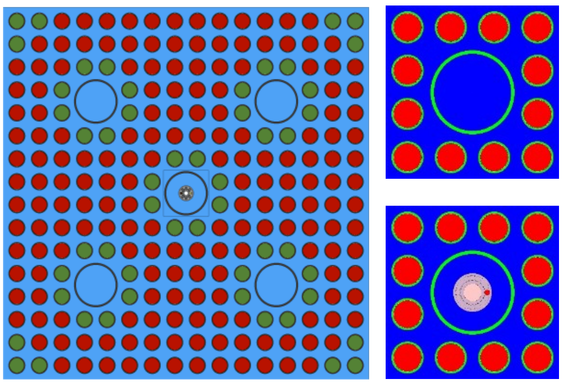

Fig. 1. Explicit modeling of instrumented fuel assembly

At first, it is checked whether these assumptions are valid for cobalt emitter of not, using MCS 2D FA calculation [5]. It is tabulated that the multiplication factors (k_{inf}) of instrumented FA using only IT, ICI without SPND, and ICI with cobalt SPND. As a result in Table I, the effect of actual installation of ICI and SPND is not negligible for k_{inf} values.

Table I: k_{inf} decrement of instrumented FA
(MCS, 2D 16x16 FA, 0 gwd/mt)

Case	k_{inf}	Diff. vs IT
IT	1.41620± 8 pcm	-
ICI w/o. SPND	1.41019 ± 7 pcm	-601 pcm
ICI with SPND	1.40941 ± 8 pcm	-679 pcm

2.2.2. MOC calculations and resonance treatment

Most lattice codes can model the pin-cell with concentric geometry. However, the geometry of SPND in ICI thimble has more complexity, even currently using rhodium-based ICI. In this section, it is explained how to model explicit geometry of ICI installed fuel assemblies.

To design of non-concentric geometry in pin-cell lattice, the new index system of mapping flat source region (FSR) has been appended. STREAM implements the 2-dimensional method of characteristic (MOC) calculation following densely distributed rays, including the FSR for emitter, insulator and collector, spacing 0.01cm and azimuthal and polar angle has 48 and 6 each.

For original IT model, the equivalence theory has been adjusted using background XS which is defined with emitter's geometry and number densities. Using actual model, the effective XS are updated with Calvik's two-term rational approximation solving the actual fixed source problem [6].

2.2.3. Depletion of the emitter nuclides

During the flux spectrum of fuel assembly changes over depletion calculation, it affects the effective XS of emitter nuclide, cobalt-59, shown in Figure 2.

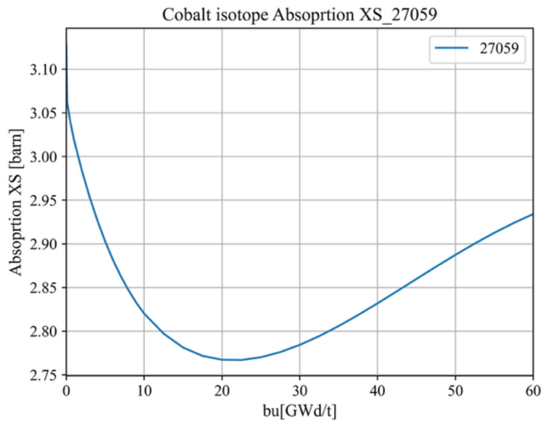

Fig. 2. One-group effective cross-section of cobalt-59

As shown in Figure 3, the number density of cobalt-59 is typically evaluated that about 10% of the cobalt-59 is transmuted to cobalt-60, and a fraction of the produced cobalt-60 subsequently undergoes beta decay to nickel-60.

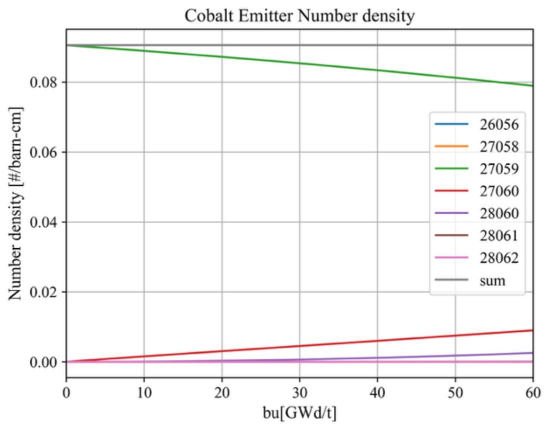

Fig. 3. Number density of cobalt isotopes (in barn)

2.3. APR1400 Whole-core depletion

In this section, the methodology and results of the whole-core simulation for the APR1400 initial core are presented. The core originally exhibits a bottom-skewed axial power shape, which provides insight into the extent of emitter depletion effects.

2.3.1. Fuel loading configuration

The lattice analysis results of the fuel assembly, calculated as described above, were extended to branch calculations of the hot-state case matrix. For each fuel assembly, three geometrical configurations—bald instrument tube (IT), ICI without SPND, and ICI with SPND—were modeled, so that they can be axially stacked in RAST-K.

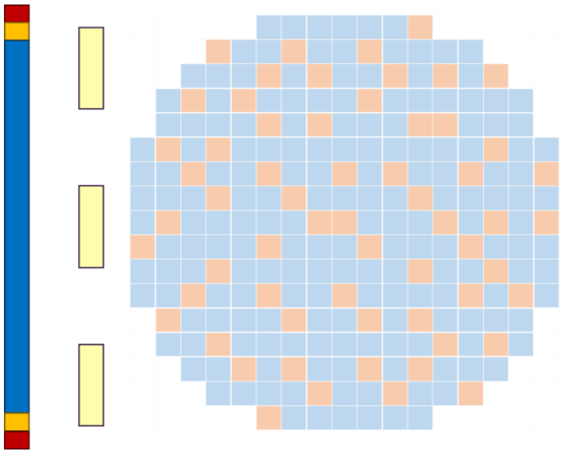

Fig. 4. SPND and ICI loading configuration (APR1400)

Figure 4 illustrates the axial configuration of the yellow-colored SPND positions (left) and the radial arrangement of the orange-colored ICI positions (right). In one ICI thimble, there're 3 axially positioned SPNDs which are top, center, and bottom SPND.

2.3.2. Depletion calculation results

The ICI thimbles, as actually installed in the center of the instrumentation tubes, influence the neutronics results by reducing the amount of moderator and through neutron absorption by the emitters. The 600-pcm reactivity loss in the instrumented fuel assembly, as shown in Table I, impacts the overall core criticality. Figure 5 illustrates the corresponding effects in the CBC of the actual ICI core (labeled as ExpICI), showing a reduction of 7 ppm at the beginning of cycle (BOC) and 56 ppm at the end of cycle (EOC). Figure 6 shows the axial shape index (ASI) results of original core and actual ICI core.

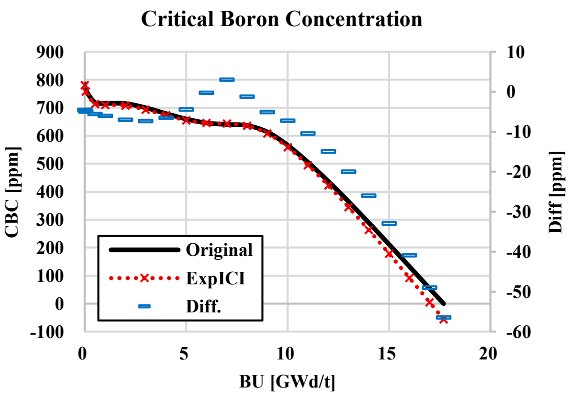

Fig. 5. Critical boron concentration of ICI loading core

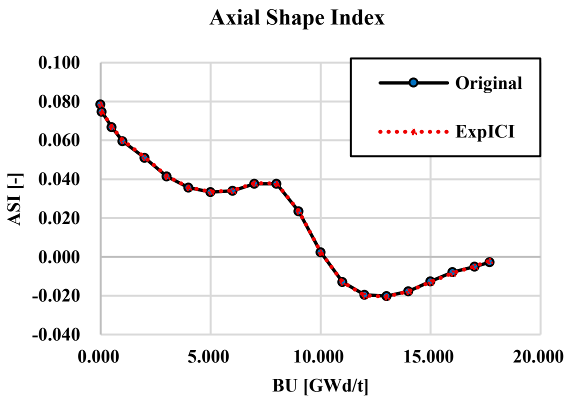

Fig. 6. Axial shape index of ICI loading core

2.3.3. Detector signal depletion effects

Using the target depletion module in RAST-K, the initial material in the guide tube is irradiated by the local neutron flux. The depletion of the target material is calculated by solving the Bateman equations using the CRAM method [7]. Figure 7 illustrates the radially averaged depletion of the cobalt-59 emitter nuclides. The top-installed SPNDs experience less depletion due to the bottom-skewed axial power shape during the most of power cycle.

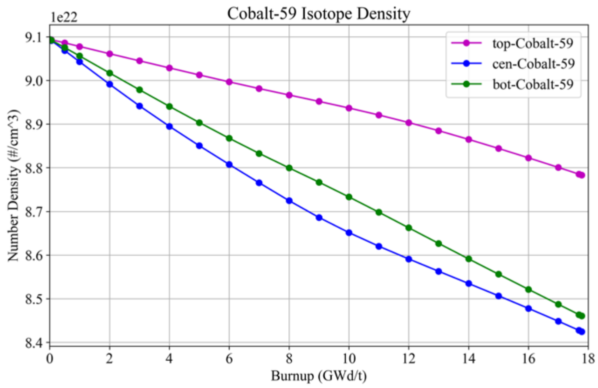

Fig. 7. Depletion of cobalt-59 with respect to neutron absorption

The overall effects of the power shape and emitter depletion from BOC to EOC are reflected in the absorption reaction rates, as shown in Figure 8. The dotted lines represent the absorption reaction rates calculated using the initial number density of cobalt-59 ($N_{det}^{(1)}$), while the solid lines represent the depletion-affected reaction rates, calculated using the burnup-dependent number density of cobalt-59 ($N_{det}^{(\tau)}$), at burnup step τ.

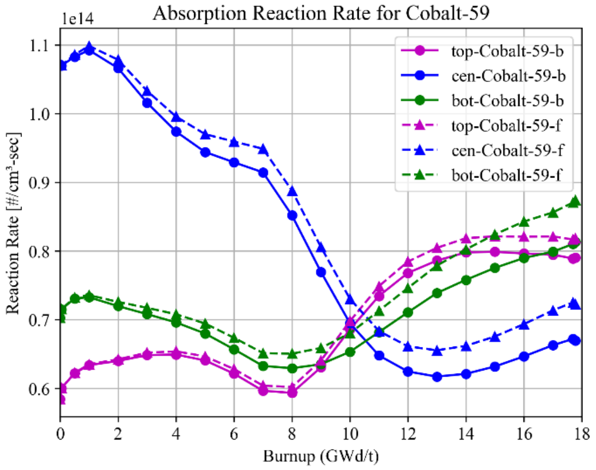

Fig. 8. Absorption reaction rates of cobalt-59 emitter

The depletion effect of reaction rates and signal ASI of each SPND are tabulated in Table II. Signal ASI, illustrated in Figure 9, is

$$Signal\ ASI = \frac{RR^{bot} - RR^{top}}{RR^{bot} + RR^{top}} \quad (2)$$

where RR^{bot} and RR^{top} are summation of bottom and top reaction rates.

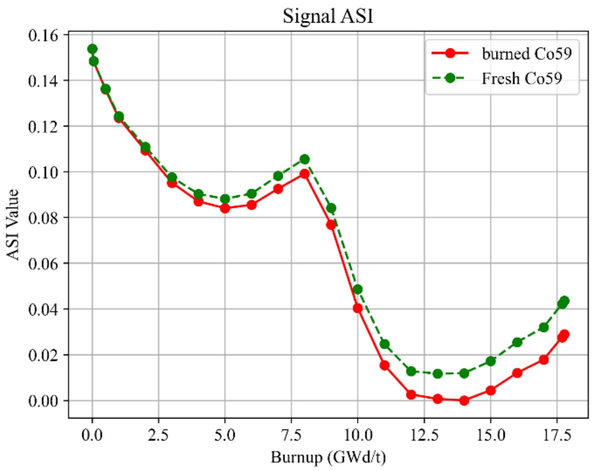

Fig. 9. Signal ASI of burnup dependent emitter and independent emitter

Table II: Depletion effect of detector signal at EOC (Radially averaged)

Result	Burnup effect at EOC
Top SPND	-2.5 [%]
Center SPND	-7.4 [%]
Bottom SPND	-7.7 [%]
Signal ASI	-0.02 [-]

2.3.4. Beta decay of Cobalt-60

The neutron-absorbed cobalt-60, from burned emitter has half-life as 5.26 years, generates the additional current from spontaneous beta decay within whole designed fuel cycle. The beta decay rate is simply formulated that,

$$R_\beta(t) = \lambda_\beta N(t)\ [\#/\text{cm}^3\text{-sec}] \quad (3)$$

where λ_β is beta decay constant. To match the order of beta decay and absorption reaction rate, $N(t)$ is used in the number density. Figure 10 shows the amount of beta particles can be clearly calculated using Eq. (3), with respect to increasing number of cobalt-60 atoms by burn-up effect. Some portions of beta particles from beta decay of cobalt-60 would be noise signal of cobalt SPND signal. In order to quantify how many beta particles are reached to collector in SPND, it is needed to analyze additional behavior of those free beta particles, using beta-enabled simulation codes like MCNP, Geant-4, or beta-S.

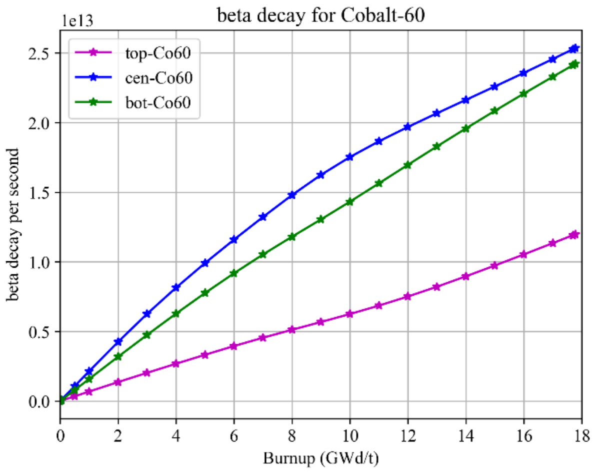

Fig. 10. Spontaneous beta decay of cobalt-60

3. Conclusion

In this study, the cobalt detector signal was calculated considering the depletion effects. A new method for tracking rays in FSR in the MOC, incorporating the actual ICI geometry, was developed in STREAM. The effective cross sections and box-to-pin factors of the emitter nuclide were transferred to RAST-K based on the conventional case matrix and burnup steps. RAST-K performed whole-core simulations of the ICI-deployed core using the newly developed depletion chain for the emitter nuclides. From the depletion effects on the number density and absorption cross section of cobalt-59, it was found that the ASI signal was overestimated by approximately 0.02.

It is difficult to directly conclude that these results correspond to the actual 'detector signal' of SPNDs, since not all neutron-absorbed cobalt atoms generate measurable electronic signals. In a cobalt detector, the detector response is influenced by beta particles from cobalt-60 decay and pair production induced by gamma rays.

To analyze the behavior of these beta particles and gamma rays, the neutron flux incident on the emitter surface should first be evaluated using Monte Carlo codes. Subsequently, a photoelectric physics code can be applied within the insulator region to determine how many beta particles reach the collector for a given neutron source. By tabulating the probability of this reaction-to-signal ratio (RSR), the results of this study can be further refined to represent the actual 'detector signal'.

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