

# Isotope Inventory Management Code System for Spent Fuel Assembly Analysis

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## 1. Introduction

This paper presents the isotope inventory calculation procedure for the management of spent nuclear fuel assemblies. The management of spent nuclear fuel is important in the safety of the back-end nuclear fuel cycle. The prediction of isotope inventory in spent nuclear fuel is required to determine radioactivity, decay heat, neutron and gamma sources, among which are parameters of spent fuel assemblies stored at the interim storage facility.

Previously developed code systems suffer from a number of challenges. The STREAM-SNF code has a high accuracy of providing the source term results for about 1500 to 1600 isotopes and could consider realistic and detail irradiation history from three-dimensional (3D) core simulation conditions. However, STREAM-SNF performs calculation based on two-dimensional (2D) fuel assembly models [1][2]. The nodal code RAST-K has the high performance in terms of speed; however, it could only provide 41 isotope information [3]. Therefore, in this work, a new code system is proposed and developed to have both the advantages of STREAM-SNF and RAST-K: accuracy and speed. Section 2 introduces the code system and its methodology (interpolation method with power correction factor), and section 3 shows the verification result with four test cases.

## 2. Methods

The main workflow of the code system is presented in this section. Fig. 1 shows the flow chart of the isotope inventory management code system. The calculation of isotope inventory is based on interpolation of the number densities generated by history branch calculation in STREAM, and history index calculated by three-dimensional (3D) reactor core simulation in RAST-K. Moreover, power correction factor is considered during the interpolation to correct the effect of decay by different time intervals between history branch calculation and the 3D core simulation. In addition, the calculation module of isotope inventory and source terms from STREAM-SNF are adopted in RAST-K. This feature has two main benefits: (1) it considers the direct 3D core simulation condition by using the history indexes and (2) it supplies about 1,500 isotopes inventory information in nodal code.

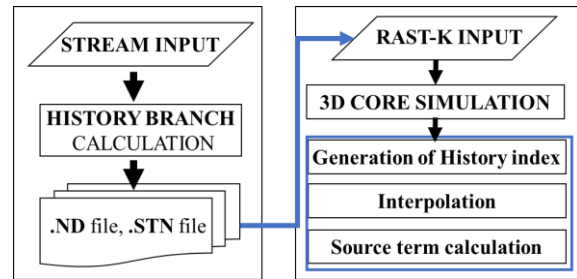


Fig. 1. Flow chart of isotope inventory management code system

### 2.1 Management code system

The STREAM and RAST-K codes are used for inventory calculation. The 3D core simulation is performed by STREAM/RAST-K two-step approach. STREAM is a lattice physics code and generates cross section (XS) and number density file by branch calculation. Number density file is used for interpolation method during RAST-K source term calculation. Interpolation method is performed in a similar way as the XS feedback. The difference is that it considers the history index during the interpolation instead of the current condition of core. History index is calculated to reflect the operating condition. In this paper, three history indexes are considered: moderator temperature, boron concentration and fuel temperature. The number density interpolation accounts for the power correction factor to consider the decay effect between isotopes in the number density file (which is the base of the interpolation) and from the 3D core simulation. This is because, the power used in the branch calculation is different from the axial node power in the 3D core simulation. Also, certain actinides have high sensitivity to the power. RAST-K generates the number density by CRAM method for about 41 isotopes without considering the power correction factor [3].

### 2.2 Calculation method of isotope inventory

This section describes the interpolation method and power correction factor. The interpolation method is used on all the isotopes except for the 41 isotopes which are shown in Table I. Lagrange interpolation method is employed and three history indexes are used instead of

current conditions. History index is calculated by equation (1).

$$h(\text{parameter}) = \frac{\sum_{i=1}^n \text{parameter}_i \Delta t_i}{\sum_{i=1}^n \Delta t_i} \quad (1)$$

where,  $h(\text{parameter})$  is the history index of parameter,  $i$  is  $i^{\text{th}}$  burnup step and  $\Delta t_i$  is time interval. Three parameters (boron concentration, moderator temperature and fuel temperature) are considered. Fig. 2 presents the difference between history index and instantaneous boron concentration. During the interpolation, cumulative operating conditions (history indexes) are considered instead of the direct instantaneous condition.

Power correction factor (PCF) is considered to correct the decay effect between isotopes in the number density file and the 3D operating condition. PCF is calculated by Equation (2) [4].

$$PCF = \frac{N_{\text{operate}}}{N_{\text{branch}}} \quad (2)$$

where,  $N_{\text{operate}}$  is number density following the operating condition and  $N_{\text{branch}}$  is number density calculated by history branch calculation. The number density depends on the time interval. Equation (3) [4] presents concentration which could be used instead of  $N$  in equation (2) [4][5].

$$\Delta C^j = \mu^j \cdot F(1 - e^{-\lambda^j t}) = \alpha * R_{\text{power}} * [1 - e^{-\lambda^j t}] \quad (3)$$

where,  $R_{\text{power}}$  is the ratio of operating power density compared by branch power density,  $\alpha$  is proportion rate,  $C$  is concentration,  $F$  is fission rate,  $j$  is  $j^{\text{th}}$  isotope and  $\mu$  is fission yield. Fig. 3 presents the power correction factor calculated by equation (2). Relative power is calculated by  $P_{3D \text{ nodal}} / P_{2D \text{ branch history}}$ . The '[REF]' label means the reference ratio between number densities calculated by 3D simulation and 2D lattice code. The '[PCF]' is the power correction factor calculated by equation (2). The relative error between reference and calculation value is less than 1.02 %.

Table I: Isotope list generated by CRAM method

Isotopes	I-135, Xe-135, Nd-147, Nd-148, Nd-149, Pm-147, Pm-148, Pm-149, Pm-148m, Sm-147, Sm-148, Sm-149, Gd-152, Gd-154, Gd-155, Gd-156, Gd-157, Gd-158, Gd-160, U-234, U-235, U-236, U-237, U-238, Np-237, Np-238, Np-239, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Pu-243, Am-241, Am-242, Am-243, Am-244, Am-142m, Cm-242, Cm-243, Cm-244
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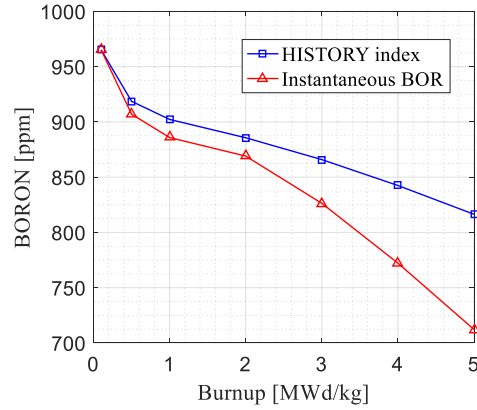


Fig. 2. History index and instantaneous boron concentration

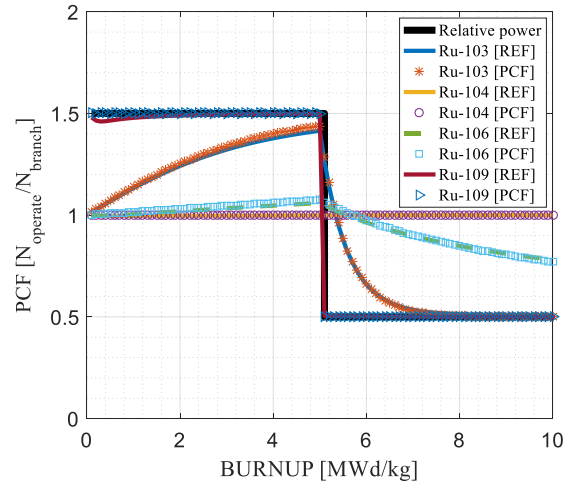


Fig. 3 Power correction factor of Ruthenium

### 3. Verification with STREAM-SNF

In this section, four different cases are tested to verify the developed code system. Westinghouse type 14 by 14 fuel assemblies are used. Fig. 4 shows the layout of the fuel assembly.

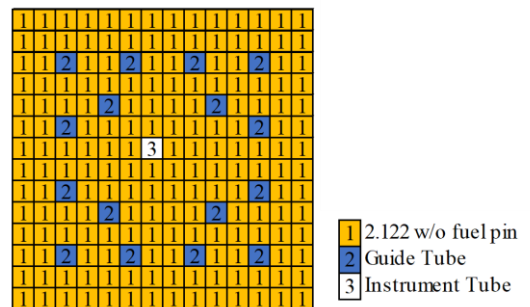


Fig. 4 Layout of 14 by 14 fuel assembly

## 2.1 STREAM-SNF

STREAM-SNF is employed to verify the predictions of the isotope inventory code system. STREAM-SNF predicts pressurized water reactor (PWR) uranium dioxide (UO<sub>2</sub>) spent nuclear fuel isotopic inventory [2]. CRAM method is adopted in STREAM-SNF with up to 1,600 isotopes. In addition, STREAM-SNF has been validated with post irradiation examination data obtained from Takahama-3, Calvert Cliffs and GKN II PWRs and most of the actinides and fission products are within  $\pm 7\%$  of measured data, on average [2].

### 2.1 Verification results

In this section, source term calculation results are presented and designated as CASE01 to CASE04. CASE01 to CASE04 are four different assembly. different Four cases are set with penalizing and changing operating conditions as the burnup proceeds. Fig. 5 presents the power operating condition of CASE01 to CASE04. Fig. 6 contains the boron concentration condition of the four cases and Fig. 7 is the fuel temperature operating condition. Comparing those three figures, it can be seen that the moderator temperature does not change much as the fuel temperature and boron concentration. Moderator temperature conditions are within 582.11 K to 582.12 K. Height of fuel assembly axial node is set as 15.33 cm and the discharged burnup is 15,000 MWd/kg. During the RAST-K nodal calculation, one assembly axial node is simulated with reflective boundary condition. In addition, transient samarium and transient xenon conditions are used.

Fig. 8 presents the relative error of source term calculation results. Source term calculation is performed for mass, activity, decay heat and gamma power. Reference result is calculated by STREAM-SNF and the calculation result comes from RAST-K. Despite the fact that the CASE01 to CASE04 are penalizing, the relative error of source term calculations is within  $\pm 2\%$ .

Fig. 9 and Fig. 10 present the detail results of source term calculation. 30 isotopes are compared. The total mass of CASE01 is 1.91454E+04 g, CASE02 is 1.94237E+04 g, CASE03 is 1.95041E+04 g and CASE04 is 1.92042E+04 g. The maximum difference of 8 g occurs in case of U-238. Although the absolute error is high, the relative error is small (0.04 %).

Table II shows the simulation time per fuel assembly axial node. Since the STREAM-SNF approach involves depletion calculation with power history information from RAST-K, the interpolation method adopted in RAST-K is more computationally efficient.

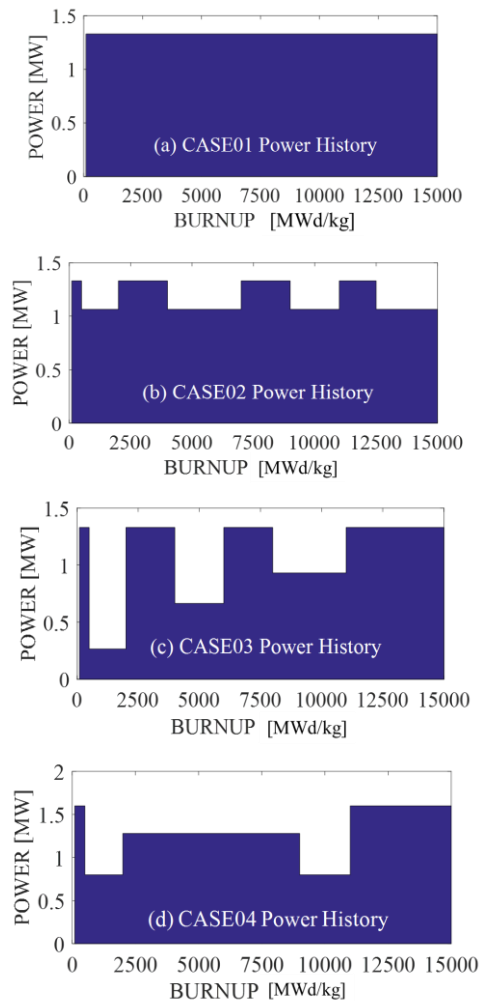


Fig. 5. Power operating condition of CASE01 to CASE04

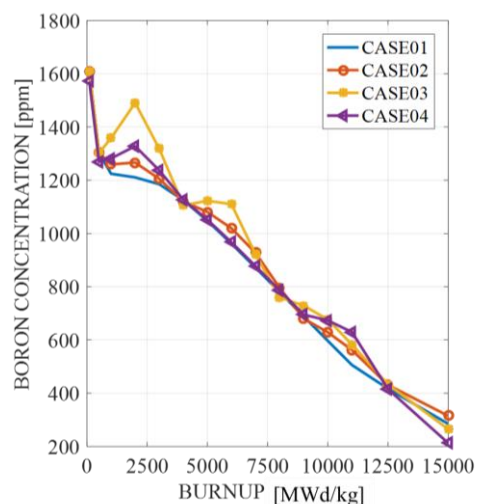


Fig. 6 Boron operating condition of CASE01 to CASE04

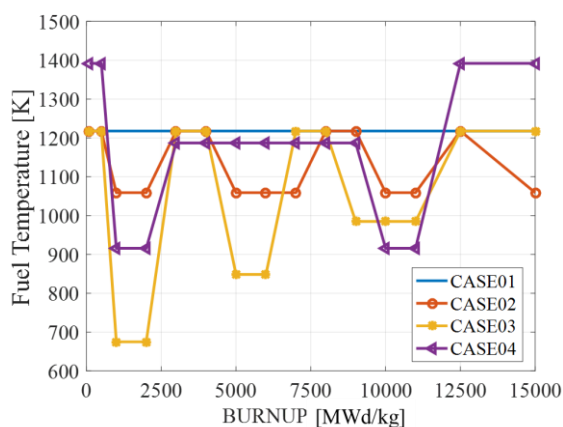


Fig. 7 Fuel temperature operating condition of CASE01 to CASE04

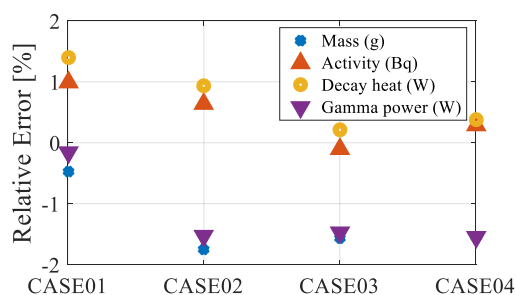


Fig. 8 Relative error of source term calculation results: mass, activity, decay heat and gamma power

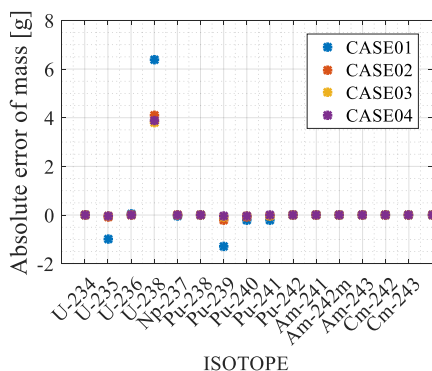


Fig. 9 Absolute error of mass in each case

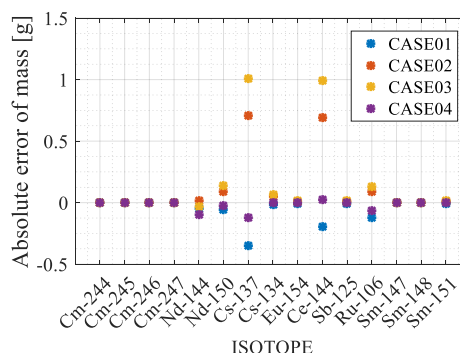


Fig. 10 Absolute error of mass in each case

Table II: Computation time comparison.

	STREAM-SNF	RAST-K
CASE01	684.962	0.439
CASE02	678.371	0.476
CASE03	678.070	0.403
CASE04	684.362	0.426

### 3. Conclusions

This paper presents the isotope inventory calculation code system for management of spent nuclear fuel assemblies. Lagrange's interpolation method and power correction factor are used to predict the isotope inventory in a nodal code, RAST-K. The source term calculation is verified with STREAM-SNF. Four cases are tested, and relative errors of source terms are within  $\pm 2\%$ . Important actinides and fission products are analyzed with maximum relative error of 0.4%. In addition, the proposed code system could reduce the computation time by three orders of magnitude during depletion and supplies up to 1,600 isotope inventory. Future work is to validate the code system with measured data.

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