Uncertainty Analysis for Graphite Isotope Ratio Method (GIRM) in a HANARO Simulation

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INTRODUCTION

DPRK possesses plutonium produced at a graphite-moderated reactor for weaponization purposes. It poses a significant threat to international security. [1] Therefore, accurately predicting plutonium production becomes crucial to indicate denuclearization progress. The Graphite Isotope Ratio Method (GIRM), developed by PNNL (Pacific Northwest National Lab) in the 1990s, provides a means to predict plutonium quantities by correlating indicator nuclides isotope ratio within graphite impurities, even in cases where detailed operational histories are available. [2-5]

To validate GIRM, the experiments have been conducted at the HANARO, and it is crucial to analyze both errors experimental and simulation errors. This study focuses on investigating errors associated with manufacturing tolerance and stochastic error. Boron, Iron, Titanium, Tungsten, and Uranium were used as indicator nuclides in previous studies. [3] Regression analysis was conducted to estimate the correlation between the isotope ratios of indicator elements and cumulative plutonium. Additionally, the relative error between predicted and calculated values was analyzed.

METHODS AND RESULTS

Uncertainty factors were defined as stochastic error of MC code and manufacturing tolerance of experiment instruments. One hundred independent depletion simulations were conducted for each uncertainty factor. The predicted line using polynomial regression was drawn based on a correlation between the isotope ratio of indicator elements and the amount of plutonium. The uncertainties were estimated through analysis of the distribution of residuals between the predicted and sampled data.

❖ HANARO reactor

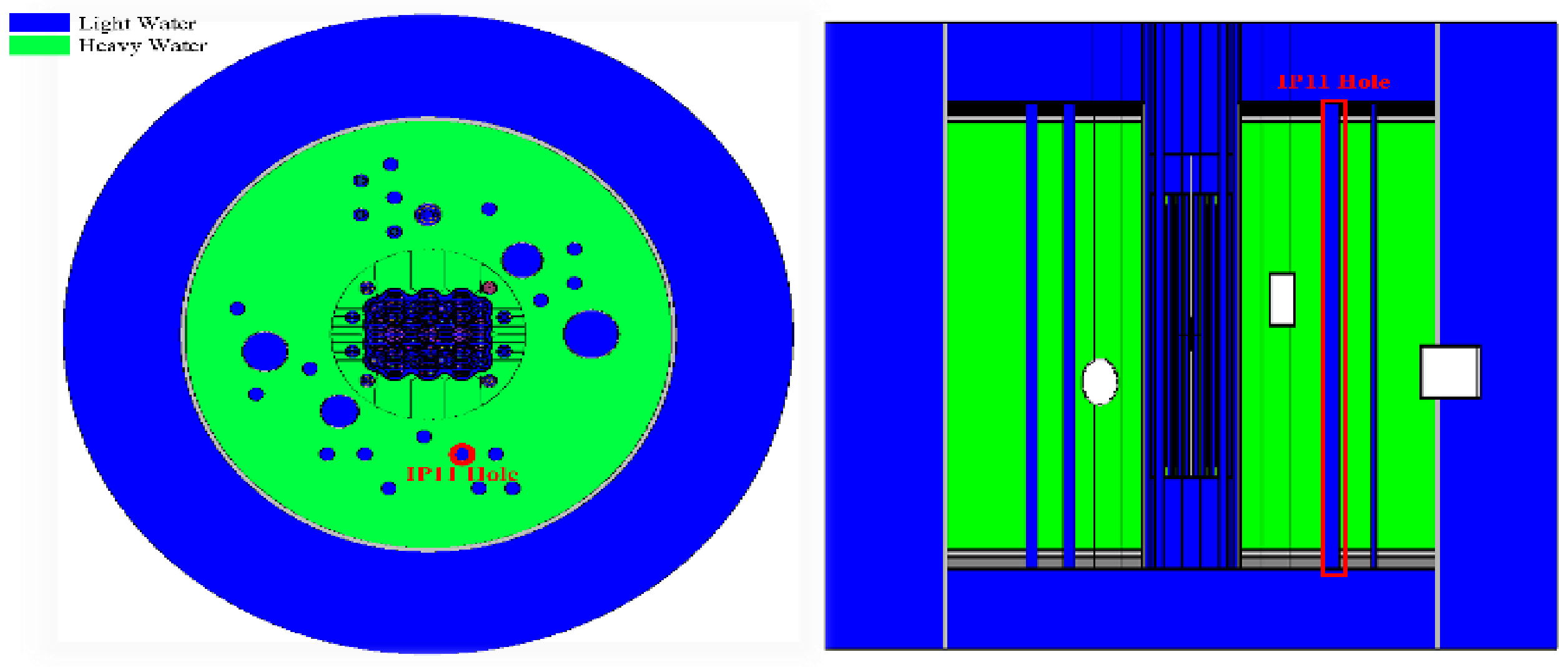

Fig 1. View of HANARO reactor (a) radial view of a full core, location of IP11 hole, (b) axial view, location of IP11 hole

The neutron irradiation experiments are conducted in an IP11 hole in the reflector region because the size of specimens is small, and parts of specimens are withdrawn during the experiments. Fig.1 shows the position of the IP11 hole, which is the experiment site.

❖ Experiment instrument specification

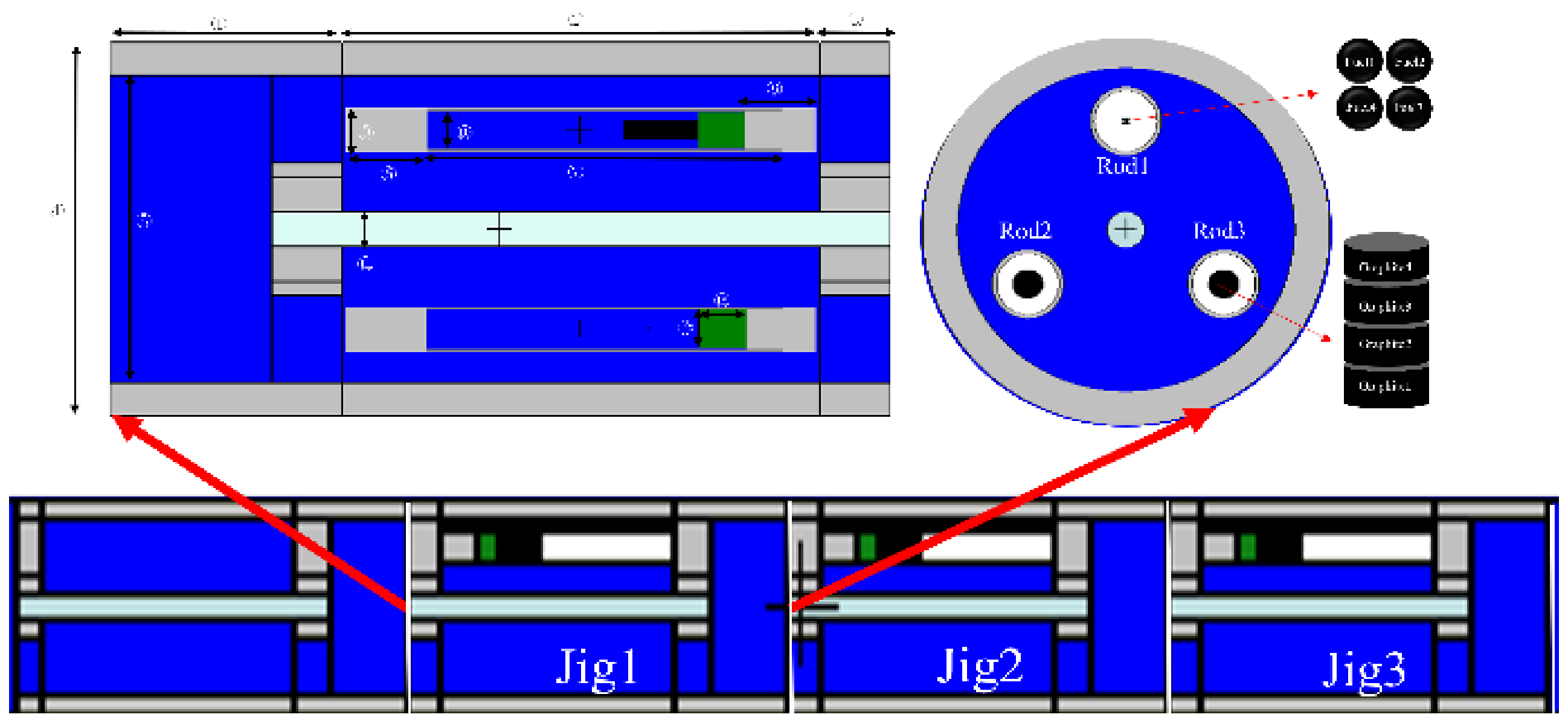

Fig 2. Experimental instruments (Rig assembly) and internal structure (Jig and rod, specimens) geometry specification, index of tolerance parameters specification

❖ Polynomial Regression

Function f(x) represents the mass density of plutonium. X is the isotope ratio data of an indicator element obtained from McCARD. In this study, the regression order is set to 3rd as Eq. (1).

$$f(x) = \sum_{i=0}^{3} a_i (\log x)^i \tag{1}$$

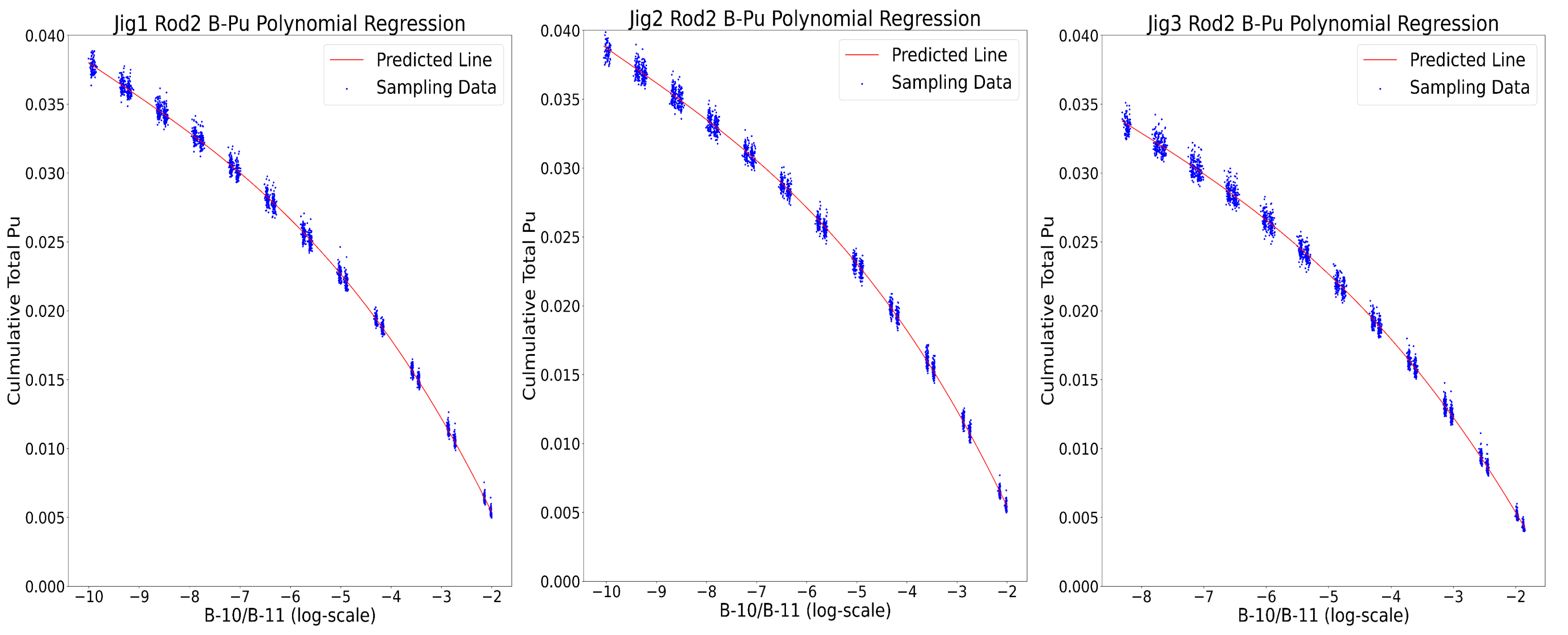

Fig 3. Prediction line using 3rd polynomial regression and B-10/B-11 sampling data by stochastic and manufacturing tolerance influence.

❖ Stochastic error of MC code and Manufacturing tolerance of experimental instrument

Normalized root mean square error (NRMSe) was used to estimate the distribution of residuals and is shown in Eq (2)

$$NRMSe = \sqrt{\frac{1}{n-1}\frac{\sum_i^n (y_{p,i} - y_{e,i})}{\overline{y_e}^2}} \tag{2}$$

y_p is the predicted cumulative plutonium mass density and y_e is the sampled cumulative plutonium mass density obtained from McCARD. The NRMSe for each indicator element sampling data, ranging from 28 to 336 days.

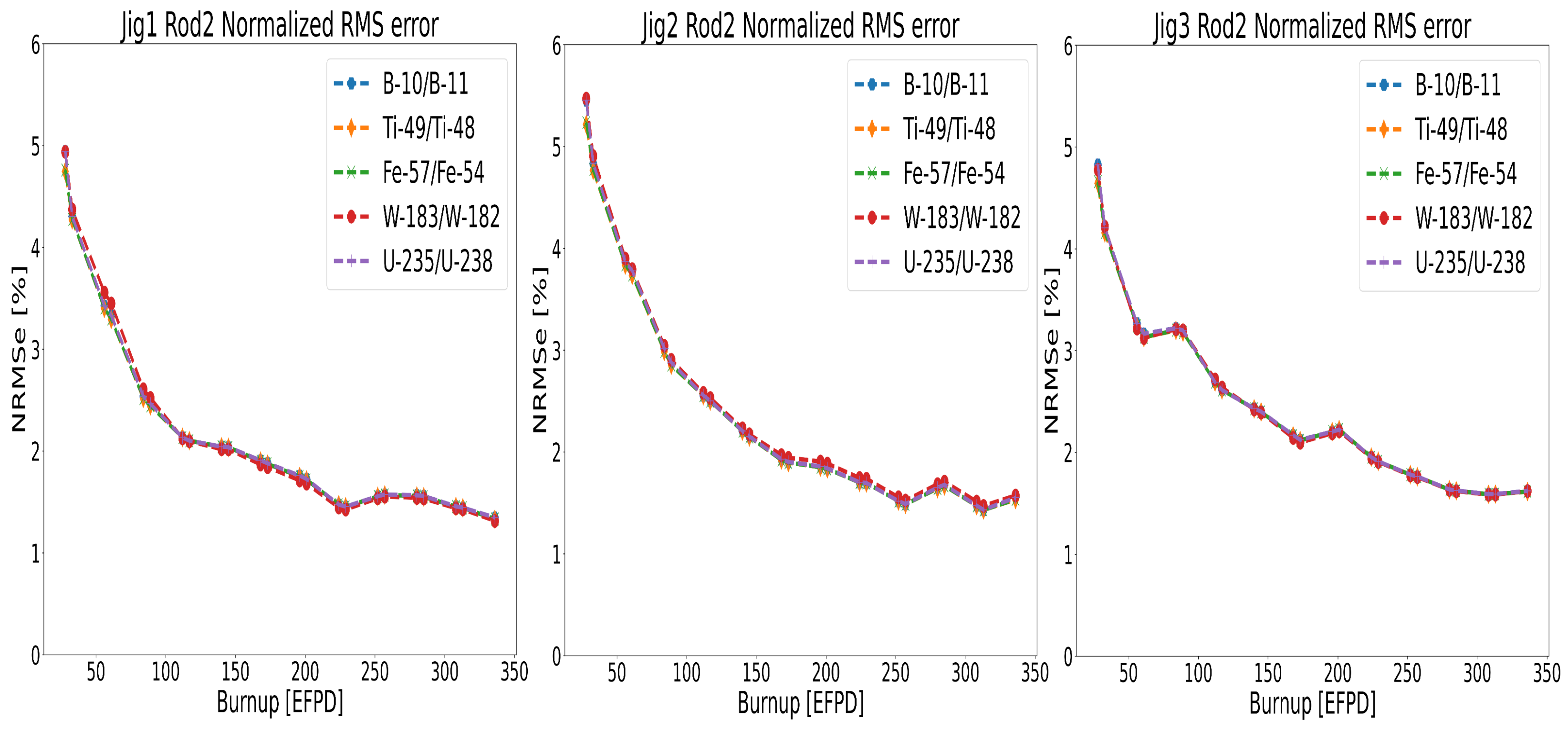

Fig 4. Comparison of NRMSe of total indicator nuclides by stochastic error by operation

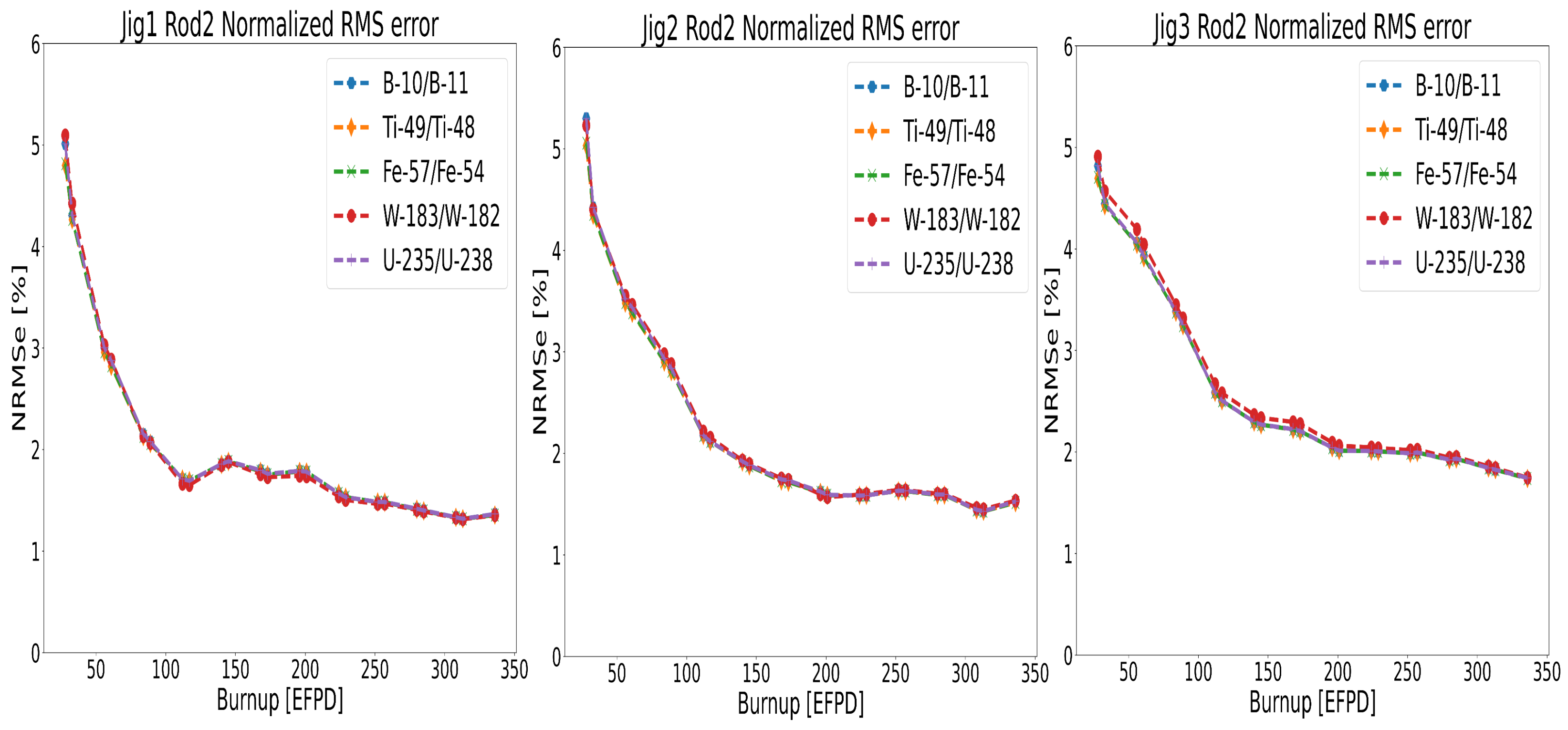

Fig 5. Comparison of NRMSe of total indicator nuclides by stochastic error and manufacturing tolerance by operation

CONCLUSION

In this study, the sampling data obtained from depletion calculation using McCARD were compared to the predicted data derived from a polynomial regression function with a logarithmic transformation. The NRMSe by statistical factor ranged from approximately 5 to 6 % at 28 days and decreased to about 1% by 336 days independently of indicator elements. Furthermore, The NRMSe resulting from the stochastic error of MC code and manufacturing tolerance factors were comparable to that of the stochastic error alone. It was estimated that the influence of the stochastic error factor is more significant than that of the manufacturing tolerance factor. Therefore, it was concluded that the influence of the manufacturing tolerance factor is negligible, and total uncertainty could be described as shown below in Eq (3). σ_r is uncertainty stochastic error and σ_r is uncertainty by manufacturing tolerance.

$$\sigma^2 = {\sigma_r}^2 + {\sigma_t}^2 \approx {\sigma_r}^2 \tag{3}$$

Furthermore, it is planned to evaluate how the covariance of nuclear cross-sectional data is going to impact the final experimental uncertainty

Acknowledgments

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