

Characterization of Spent Fuel Parameters using Non-destructive Assay and Machine Learning

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1. Introduction

Spent fuel is an important subject of verification under nuclear safeguards. The amount of nuclear material it contains and the diversion of nuclear material must be verified. As part of the verification, characterization of operator-declared information such as initial enrichment (IE), burnup (BU), and cooling time (CT) is necessary [1, 2]. Conventionally, non-destructive assay (NDA) systems are used to characterize the spent fuel [3, 4, 5] and thereby validate the operator-declared information based on the measured data. This approach has the limitation of relying on operator-declared information. Therefore, it is important to independently estimate spent fuel parameters from measured data rather than depending on it. However, gamma-ray and neutron measurement data have complex correlations with spent fuel parameters, making their analysis challenging [6]. To address this complexity, machine learning is used.

In this paper, we evaluate the capability to estimate the IE, BU, and CT of pressurized water reactor (PWR) from simulated gamma energy spectra and total neutron count rates obtained with our spent fuel characterization system. In the analysis process, machine learning techniques are utilized for the estimation. This study results suggest that machine learning-based analysis using gamma-ray energy spectra and total neutron count rates can successfully estimate the IE, BU, and CT of spent fuel.

2. Methods and Results

2.1. Detector response Calculation (Forward)

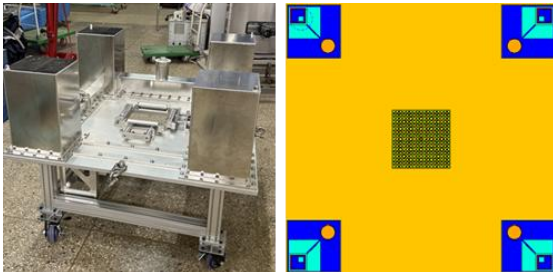


Fig. 1. Prototype and cross-sectional view of the proposed spent fuel characterization system.

We simulated the verification of PWR spent fuel assemblies using the developed spent nuclear fuel characterization system. In the system, CZT (Cadmium Zinc Telluride) detectors were used for gamma-ray and

stilbene detectors for neutron. The fuel assembly was modeled as an 17x17 ACE7 type PWR assembly. Considering the general operating history of PWR fuel, depletion calculation were performed under randomly specified conditions: IE of 3–5%, BU of 24–60 GWD/MTU, and CT of up to 30 years. Gamma-ray and neutron emission spectra (ϕ_i) is used to simulate gamma-ray energy spectra and neutron count rates (C_i). Here, i represents the data sample index.

$$C_i = \phi_i \times R \quad (1)$$

MCNP 6.2 code was used to simulate the detector response. Absolute detection efficiency (R) of gamma-ray and neutron is calculated by pulse height tally (F8) and PTRAC file processing. By combining emission spectra and absolute efficiency, gamma-ray energy spectra and neutron count rates were derived.

2.2. Estimation using machine learning model (Backward)

The XGBoost (eXtreme Gradient Boosting) algorithm was used to estimate the IE, BU, and CT of spent fuel. The dataset consisted of 50,000 samples of gamma-ray energy spectra and neutron count rates from spent fuel with diverse combinations of operating history. The dataset was split into training (80%) and test (20%) sets, and k-fold cross validation was applied for hyperparameter tuning to ensure model robustness.

Gamma-ray spectra and total neutron count rates were used for input features of model. IE, BU, and CT of spent fuel were the target variables. All input variables were normalized to stable estimation. Estimation performance was evaluated using relative root mean square error (RRMSE) as shown in equation 2.

$$RRMSE = \sqrt{\frac{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (\hat{y}_i)^2}} \quad (2)$$

Table 1. RRMSE of true and estimated values of IE, BU and CT using gamma-ray data only.

Spent fuel parameters	Estimation performance (RRMSE)
Initial enrichment (IE)	0.086
Burnup (BU)	0.006
Cooling time (CT)	0.007

Table 1 shows the estimation results using gamma-ray data only. BU and CT were estimated with low RRMSE, demonstrating reliable estimation performance. However, the estimation of IE was challenging with gamma-ray data. This is because most of the gamma-ray emitted by spent fuel are related to fission products, which are not affected by the IE and depend on the total energy produced by fission. The estimation performance of IE can be improved by incorporating neutron data.

3. Conclusions

We demonstrated a machine learning-based methodology for estimating the IE, BU, and CT of spent fuel. In the forward framework, detector responses were evaluated by combining the emission spectra with the absolute detection efficiency of the system. In the backward framework, machine learning model was developed using the XGBoost algorithm and its estimation performance was evaluated.

The results show that BU and CT can be reliably estimated using gamma-ray data with low RRMSE values. In contrast, IE estimation is inherently limited with gamma rays due to their weak correlation. This limitation can be effectively addressed by incorporating neutron data, which provide complementary information.

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