Advanced Analysis of the IAEA Fork Detector Data for Partial Defect Verification

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Abstract

In recent years, a new advanced analysis approach has been developed for fork detector data, whereby the neutron and gamma radiation measured by the fork detector are compared with the values calculated by the ORIGEN depletion code using the operator's declaration of the spent fuel assembly history. The IAEA's Department of Safeguards (SG) has applied this algorithmic analysis procedure on a large set of PWR and VVER-1000-type spent fuel assemblies verified with the IAEA/SG fork detectors.

The analysis shows the standard deviation of the difference between the measured and calculated neutron and gamma radiation to be 8% and 6%, respectively. Taking into consideration that the neutron radiation is proportional to the mass of the spent fuel assemblies, the IAEA is pursuing the authorization for field deployment of the fork detector for partial defect verification of PWR-type spent fuel assemblies. Details of the analysis methodology, including the normalization procedure, and the results of the analysis for a population of PWR spent fuel assemblies will be presented.

1 Introduction

Spent fuel assemblies (SFAs) contain irradiated direct use material subject to international nuclear safeguards. After they are removed from the core, usually after being fully burned, SFAs reside in the spent fuel pool to cool down before being loaded into casks and sent to interim dry storage or to an encapsulation plant. Typical cooling time in the spent fuel pond spans from 5 to 40 years. The safeguards approach for spent fuel is based on the principle of maintaining continuity of knowledge (CoK) on the spent fuel assembly along the spent fuel movement path described above and to verify its integrity before it is loaded into a cask, as from this point, the spent fuel assembly is categorized as difficult to access. With spent fuel ponds in many countries reaching their design capacity, the number of SFAs transferred from wet to dry storage is increasing worldwide and is expected to continue increasing in the upcoming years. These developments have sparked a need to develop accurate and reliable spent fuel verification methods, as well as to improve existing techniques and maintaining rapid throughput [1][2].

Measurement of gross neutron and gamma emission with the fork detector (FDET) is a well-established technique for spent fuel verification [3]. Because of its robustness, portability, simplicity and short measurement time, the FDET is routinely and extensively used for safeguards verification activities by inspectors in the field. In addition, its uncomplicated installation and low profile in spent fuel storage pools is appreciated by facility operators.

The large number of spent fuel assemblies to be verified requires the verification methods to be performed in automated and unattended operation. For a long time, the IAEA-developed Unattended Fork Detector Monitor (UFDM), a mobile, tamper-indicating cabinet containing a power supply and data acquisition module, was the solution of choice. Once connected to the FDET, the UFDM allows continuous data collection in unattended mode. Recently, the IAEA developed a new compact version of the UFDM system to improve its portability and use state-of-the-art data acquisition modules in the new design. Like its predecessor, the mini-UFDM is connected to the FDET in the spent fuel pond, but its form factor is such that it fits into a case that can be hand-carried.

Not only were the FDET and UFDM electronics upgraded to the current standards, but the instrument's capability to perform more sophisticated assessments was evaluated, with the aim of expanding its authorized safeguards applications. The evaluation of the IAEA FDET for partial defect verification is the topic of this paper.

2 Partial Defect Analysis

Assessing the completeness of spent fuel items (i.e., performing a partial defect test) represents the most advanced mode of FDET data evaluation and consists of comparing the neutron and gamma count rates measured by the FDET to the neutron and gamma count rates predicted by ORIGEN[1] depletion code calculations.

The ORIGEN burnup calculations are based on lattice physics, depletion modelling and detailed detector modelling and allow a physically consistent evaluation of the fork detector data. This approach is expected to be more accurate compared to the classical data analysis because it considers the detailed operating history (dates of irradiation for each cycle in the reactor core and accumulated burnup during each cycle of operation) of the spent fuel assembly and compares the measured vs. predicted count rates of the detectors. Furthermore, because there is no longer the need to keep a database of past measurements, as each individual measured assembly can be verified against the operator's declarations, the new approach has significant advantages over the classical analysis based on the FDMS (Fork Detector Measurement System) software application.

Under the framework of a cooperation agreement between the US Department of Energy and EURATOM, Oak Ridge National Laboratory (ORNL) developed a module for automated fork detector data analysis by using the ORIGEN (Oak Ridge Isotope GENeration) code from the SCALE code system, a widely used modelling and simulation suite for nuclear safety analysis and design. Called ORELLA, this module has been integrated into the Integrated Review and Analysis Package (IRAP)[6], the standard data analysis and review platform used by IAEA and EURATOM.

Running ORIGEN calculation on a large batch of spent fuel assemblies, each with its complex irradiation history, might be cumbersome due to the need to prepare several ini. files. This analysis method was made deployable at scale by 1) the availability of the ORELLA module in IRAP, 2) the definition of a universal format for the operator declarations and 3) the development of the CASCADE[2] programme for importing the operator declarations in IRAP. The process is fully automated, such that:

- Operator declarations are imported into IRAP and the .ini files for the ORIGEN calculations automatically created.

- The predicted results for each spent fuel assembly are stored together with its time-stamped measurement.
- Measured FDET results are compared to the predicted results computed by ORIGEN; both are displayed in a report for the inspectors.

The capability of this enhanced analysis of the FDET-measured data to allow partial defect verification has been confirmed and reported in several publications [4][5] based on the EURATOM instrument, but until now had never been evaluated with the IAEA FDET.

3 Methodology

The expected neutron emission rate for the i-th fuel assembly $N_E(i)$is the number of neutrons emitted by the fuel assembly as calculated using the ORIGEN depletion code on the basis of known initial enrichment, fuel design (linear mass) and irradiation history. The measured neutron count rate $N_M(i)$is the neutron count rate measured with the FDET.

A normalization factor φ is evaluated as the averaged ratio between the measured and expected neutron emissions of all the fuel assemblies:

$$\varphi = \frac{\sum_i N_M(i)}{\sum_i N_E(i)}$$

Using the normalization factor φ, the predicted neutron count rate $N_P(i)$is calculated as

$$N_P(i) = \varphi \cdot N_E(i)$$

The normalization factor accounts for neutron transport, different fuel designs and intrinsic detection efficiency.

Figure 1 shows the calibration parameters determined in seven cask loading campaigns for a total of 147 fuel assemblies, including 32 MOX assemblies. The stability of the detector response for both gamma and neutron radiation, over the full data collection time of more than six months is remarkable.

It is worth noting that in the data analysis reported in [4], the LND, Inc. Model 52110 gamma ionization chambers used in the EURATOM fork detector exhibited nonlinear behaviour as a function of the gamma exposure rate. The nonlinear response was later attributed to an insufficient electric field (voltage) leading to incomplete charge collection.

The data reported herein, collected with the ionization chamber operated at the nominal voltage, show very good linearity. For some assemblies, the electronics processing the gamma detectors saturated, as can be seen in the bottom graph of Figure 1.

The operator-inspector difference (OID) is determined as follows:

$$\mathrm{OID}(i) = \frac{N_E(i) \cdot \varphi - N_M(i)}{N_E(i) \cdot \varphi} = \frac{N_P(i) - N_M(i)}{N_P(i)}$$

The OID values serve as a measure to determine the performance of the method.

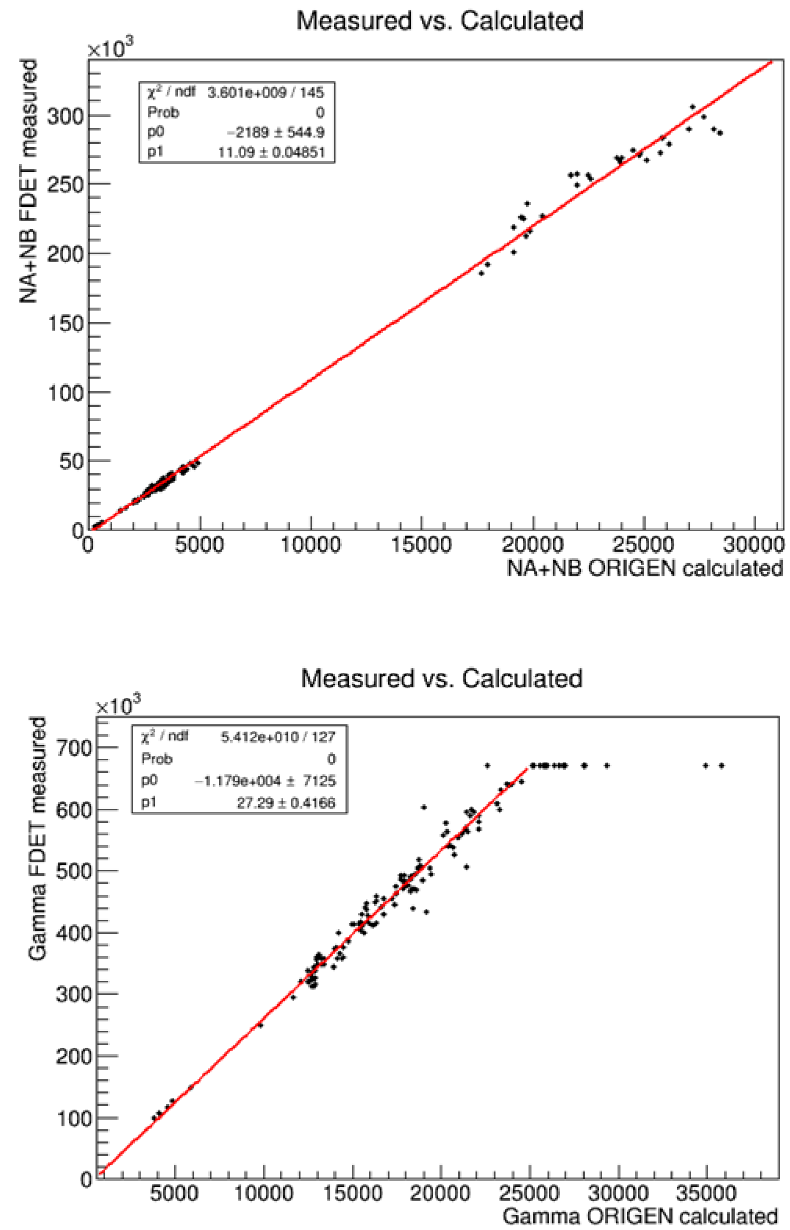

Figure 1. The FDET measured neutron (top) and gamma (bottom) count rate versus the ORIGEN calculated rates. High levels of gamma radiation from spent fuel assemblies with short cooling times caused saturation of the electronics processing the gamma signal; this can be observed in the panel on the bottom (see text).

4 Results

The analysis method was evaluated over a large set of PWR and VVER-1000 assemblies. Results of a representative set of 147 PWR spent fuel assemblies (17 x 17 lattice design) loaded during seven dry cask loading campaigns are featured herein. Figure 2 shows the distribution of the OID values for neutron and gamma counts.

For the featured population, the measured standard deviations are 5.6% and 4.5%, respectively, for the neutron and the gamma difference. Some spent fuel assemblies had cooling times of less than 4 years, which saturated the electronics unit measuring the gamma radiation. The reported RMS values exclude these SFAs.

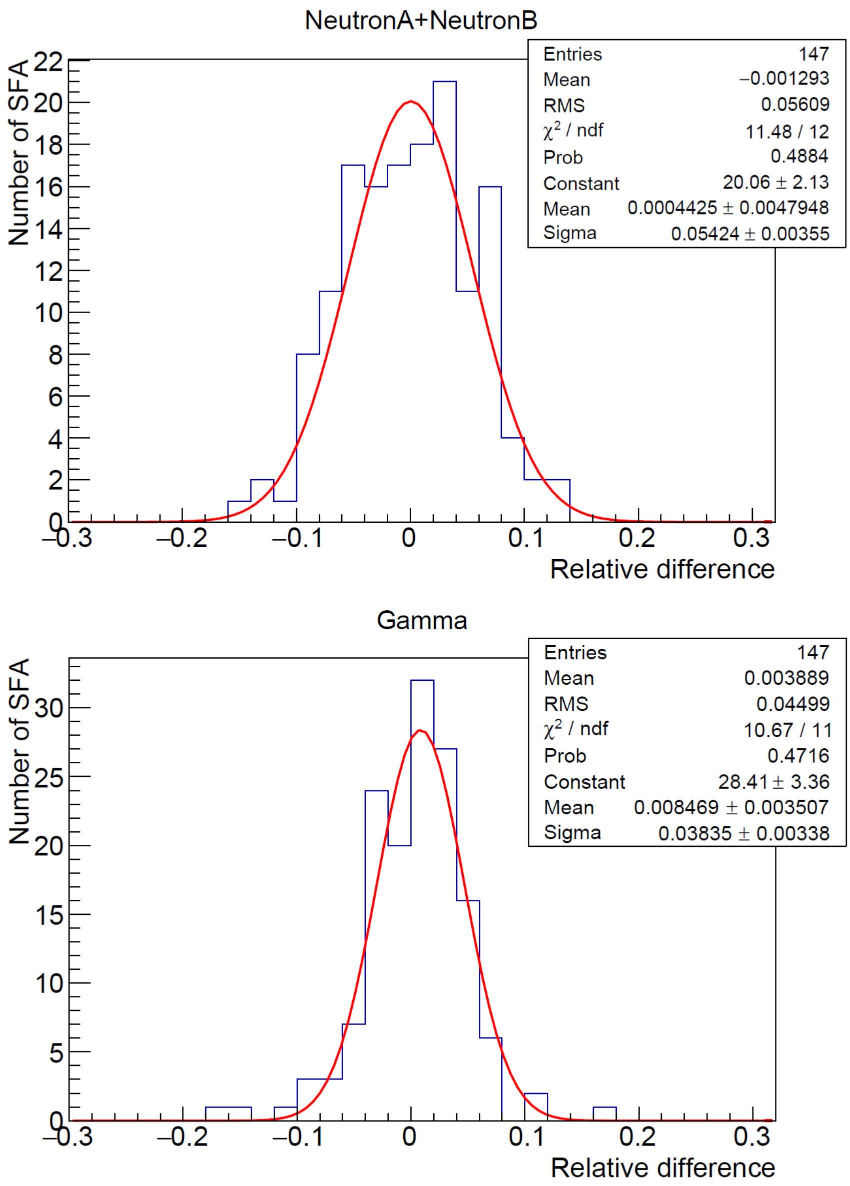

Figure 2 Distribution of the OID for neutron (top) and gamma (bottom) count rates for 147 PWR spent fuel assemblies. The standard deviations of the neutron and gamma OID distributions are $\sigma na+nb$=5.6% and $\sigma\gamma$=4.5%, respectively.

Extending the analysis to the large set of SFAs studied, the overall standard deviation values are deduced to be 8% and 6%, respectively, for neutron and gamma differences. The results are fully in agreement with the evaluation done by EURATOM (reported in [4]) and confirm that the fork detector could qualify as a partial defect tester. Expanding the fork detector's use to include partial defect verification would add a simple, low-impact instrument to the inspector's toolbox, however, its deployment for such safeguards applications would require undergoing the IAEA's rigorous internal authorization process.

5 Conclusions

FDET measurements have long been used for routine safeguards verification activities. To respond to the demand for an increasing number of spent fuel verifications, the IAEA conducted its own advanced analysis based on ORIGEN calculation on more than 1 000 spent fuel assemblies measured with the IAEA fork detector. Results on the subset of data reported in this paper are in agreement with other studies and demonstrate the suitability of the analysis for partial defect verification.

The risk of diversion, i.e., vulnerability to incorrect operator-declared values for cooling time, burnup and initial enrichment—while low—must be evaluated (and, if necessary, mitigated) within the overall safeguards approach and acquisition path analysis for the facility/state, in particular taking into consideration other means available to inspectors to independently confirm the operator declaration.

6 References

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[1] Oak Ridge Isotope Generation code calculates time-dependent concentrations, activities, and radiation source terms for a large number of isotopes simultaneously generated or depleted by neutron transmutation, fission, and radioactive decay. It is part of the SCALE code system, a widely used modelling and simulation suite for nuclear safety analysis and design that is developed, maintained, tested, and managed by the Reactor and Nuclear Systems Division (RNSD) of Oak Ridge National Laboratory (ORNL). Source: RSICC code package

[2] Centralized Automated System for Correlated Analysis and Data Evaluation