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Advancing the Fork detector for quantitative spent nuclear fuel verification

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ABSTRACT

The Fork detector is widely used by the safeguards inspectorate of the European Atomic Energy Community (EURATOM) and the International Atomic Energy Agency (IAEA) to verify spent nuclear fuel. Fork measurements are routinely performed for safeguards prior to dry storage cask loading. Additionally, spent fuel verification will be required at the facilities where encapsulation is performed for acceptance in the final repositories planned in Sweden and Finland. The use of the Fork detector as a quantitative instrument has not been prevalent due to the complexity of correlating the measured neutron and gamma ray signals with fuel inventories and operator declarations. A spent fuel data analysis module based on the ORIGEN burnup code was recently implemented to provide automated real-time analysis of Fork detector data. This module allows quantitative predictions of expected neutron count rates and gamma units as measured by the Fork detectors using safeguards declarations and available reactor operating data. This paper describes field testing of the Fork data analysis module using data acquired from 339 assemblies measured during routine dry cask loading inspection campaigns in Europe. Assemblies include both uranium oxide and mixed-oxide fuel assemblies. More recent measurements of 50 spent fuel assemblies at the Swedish Central Interim Storage Facility for Spent Nuclear Fuel are also analyzed. An evaluation of uncertainties in the Fork measurement data is performed to quantify the ability of the data analysis module to verify operator declarations and to develop quantitative go/no-go criteria for safeguards verification measurements during cask loading or encapsulation operations. The goal of this approach is to provide safeguards inspectors with reliable real-time data analysis tools to rapidly identify discrepancies in operator declarations and to detect potential partial defects in spent fuel assemblies with improved reliability and minimal false positive alarms. The results are summarized, and sources and magnitudes of uncertainties are identified, and the impact of analysis uncertainties on the ability to confirm operator declarations is quantified.

1. Introduction

Irradiated nuclear fuel is included in the range of nuclear materials under comprehensive international safeguards agreements because of its fissile material content [1,2]. Under the framework of safeguards inspectorates and nonproliferation treaties, continuity of knowledge (CoK) on previously verified irradiated fuel must be maintained to ensure the presence and integrity of the assemblies in storage. When a fuel assembly is transferred to dry cask storage or encapsulated for permanent repository disposal, independent verification measurements are needed to confirm the operator declarations and integrity for the item to ensure that nuclear material has not been diverted. The verification can be made in advance and CoK maintained until loading or until the moment of packing the assembly into a cask. For this purpose, currently adopted practices of the European Atomic Energy Community (EURATOM) and International Atomic Energy Agency (IAEA) foresee the use of the Fork detector and the digital Cerenkov viewing device (DCVD) [3].

A rapid increase in dry cask loading operations worldwide due to limited pool storage capacity has presented operational and technical challenges that require more effective and efficient safeguards inspections, including improved analysis of safeguards measurements. In addition, the spent fuel encapsulation plants and geological repositories (EPGRs) planned in Finland and Sweden will be operational in the next decade and will require enhanced levels of spent fuel assembly verification. Given the large number of fuel assemblies involved in these operations,

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the verification measurements should be performed in an automated, unattended mode [4]. Design and testing of new verification instruments is ongoing under the IAEA support program framework and in national programs in Sweden and Finland. Advanced detector technologies being investigated include passive gamma emission tomography (PGET) for verification at the individual fuel rod level [5]. Active and passive instruments are also being developed under a US Department of Energy (DOE) Spent Fuel Nondestructive Assay (NDA) project under the Office of International Nuclear Safeguards. Field test plans in Sweden include calorimetry, differential die-away self-interrogation, and differential die-away techniques [6,7] that measure fissile material characteristics. While these new technologies offer significantly advanced technical capabilities, they remain research and development prototypes with unproven reliability and performance in operational conditions, especially for application to repository projects expected to reach the commissioning phase within 5 years.

An established technology used for spent fuel safeguards measurements is the Fork detector, which is based on gross gamma-ray and total neutron counting [8]. The Fork instrument has gained widespread use since its inception in the 1980s because of its reliability, portability, speed of measurement, and simplicity. However, careful evaluation of Fork measurement data is crucial due to the sensitivity of the measured signals to initial enrichment, burnup, cooling time and fissile content (through sensitivity of the neutron measurements to subcritical multiplication). Analytical and semi-empirical methods are based on consistency within a diversified set of assemblies. These methods have been developed in the past to analyze Fork measurement data [8,9]. However, such methods do not account for important factors that affect the measurements and they have the potential to introduce large errors such as the case of assemblies with long cooling periods between subsequent irradiations. These methods also do not account for the fact that in single cask loading, the assemblies may not be sufficiently diversified in burn-up and cooling time to ensure that a meaningful consistency check can be performed. In addition to these considerations, simulation-based studies have estimated that when using these data analysis techniques, the Fork detector may not be able to detect fuel diversions of up to 50% of a spent fuel assembly if particular diversion strategies are adopted [10].

A different approach has been developed to improve the ability to use the Fork detector as a quantitative verification technique. This approach requires evaluation through comparison of measured signals against expected signals. This is calculated by a physical simulation based on operator declarations provided in records on the main attributes of a given spent fuel item. These attributes include burnup, initial enrichment and cooling time. Given the complexity of the isotopic compositions and associated gamma and neutron emission rates in a spent fuel assembly, enhanced data analysis is desired to improve the verification capability of Fork measurements.

As part of a collaboration between DOE and EURATOM, a standard data analysis module, referred to as the Oak Ridge Isotope Generation (ORIGEN) module, was developed for the automated review of Fork detector measurement data. This module [11], based on the ORIGEN burnup analysis code, has been implemented in the Integrated Review and Analysis Program (iRAP) software [12] developed by EURATOM and IAEA. ORIGEN [12,13] is part of the SCALE code system [14]. Early field testing [15–19] has demonstrated that Fork data analysis software greatly improves the accuracy and reliability of spent fuel verification.

The current research expands on these earlier studies by re-evaluating all previous measurements using updated data analysis software, and it includes additional measurement campaign data. A total of 289 assemblies measured during dry cask loading campaigns in Europe were analyzed. In addition, analysis of 50 assemblies recently measured in Sweden as part of an R&D project is also presented. An evaluation of factors influencing uncertainty in the Fork measurements and simulations was performed to quantify the ability of this approach to verify operator declarations and to develop quantitative go/no-go (pass/fail) criteria for safeguards verifications during cask loading or encapsulation. The approach adopted in this work does not seek to verify individual spent fuel attributes included as part of an operator declaration (e.g., burnup, initial enrichment, and cooling time). The approach does compare the as-provided declarations – used to compute the expected Fork detector signals for a given fuel assembly – to the measured quantities. Incorrect operator declarations or integrity-altered fuel will appear as inconsistent signals, so the operator declarations can be verified as a whole.

This approach gives safeguards inspectors the data analysis tools that provide reliable, real-time data analysis during inspections to help them rapidly identify discrepancies in operator declarations and detect potential partial defects in spent fuel assemblies with improved reliability and minimal false positive alarms. This approach can improve near-term capability with a minimal impact on current inspections or facility operations as advanced next-generation detector systems are being developed, demonstrated, and deployed over a longer timeframe.

This paper is organized as follows. Section 2 describes the Fork detector design and electronics, data acquisition system, and the ORIGEN data analysis module. This section discusses the results of instrument calibration testing and the software corrections implemented to account for observed instrument behavior. Section 3 describes the dry cask loading campaign measurements and the measurements performed in Sweden, and it summarizes the results from analysis of the measurement data. Section 4 reviews the uncertainties in the measurements, declarations, and the analysis software. Section 5 summarizes findings and indicates potential paths for further research.

2. System description

2.1. Fork detector and electronics

The Fork detector has two arms, each of which contains an ion chamber for gross gamma flux measurement (operated in current mode) and two ^{235}U fission chambers for total neutron measurement. Measurements are generally performed in water-filled ponds prior to dry storage cask loading, with both the detectors and fuel assembly under water.

In the Fork detector design currently used by EURATOM, the ion chamber and one of the fission chambers are embedded in a polyethylene block covered with a cadmium liner, and the other fission chamber is bare. The signals from the two ion chambers (one in each arm) are combined to form the total gamma signal. Similarly, signals from the two bare fission chambers are combined to form neutron channel A (neutron-A), and those from the two cadmium-covered fission chambers form neutron channel B (neutron-B). Combining signals from each arm reduces the influence of radial asymmetry in the emissions caused by burnup gradients in the assembly. The current EURATOM design uses the model 52110 gamma ion chamber [20] manufactured by LND and the model FC167 ^{235}U fission chamber manufactured by Centronic [21]. In the IAEA Fork design, all detectors are embedded in a polyethylene block without cadmium.

The Fork detector head is mounted on a stainless steel pipe through which the connecting cables are fed to the electronic unit at pond side (Fig. 1). The rear part of the Fork enclosure hosts the detector preamplifiers. In the EURATOM configuration, the neutron and gamma signals are processed by the modular unit, SMC 2100, manufactured by Freiberger Sensortechnik [22]. The same unit supplies the high and low voltages needed by the detectors and preamplifiers. The electronic unit can be sealed, enabling the system for fully unattended operation. Signals are processed in the IAEA configuration using the GRAND3 [23] or MiniGRAND electronics unit. The electric current in the ionization chamber is converted to a digital signal referred to as a gamma unit. It was observed in the measurement data analyzed in this paper that the conversion factor from the current to the digital gamma unit depends on the signal processing used in different electronics units. For example, it was observed that the gamma signals from the IAEA instruments were