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Non-Destructive Assay of Spent Nuclear Fuel Prior to Geological Disposal in Finland

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ABSTRACT

All spent nuclear fuel in Finland will be disposed of in a geological repository. Operations at the facility in Olkiluoto, Eurajoki are set to start in the coming years. Before the fuel is placed in copper canisters and disposed of in the bedrock 430 meters below ground, all fuel assemblies must be verified with non-destructive methods. Two complementary methods are chosen in Finland for this task: Passive Gamma Emission Tomography for rod-level detection of anomalies and Passive Neutron Albedo Reactivity for detecting fissile material. Together these two methods provide a reliable verification that the fuel corresponds to nuclear safeguards declarations and that all nuclear material remains in peaceful use.

1 INTRODUCTION

Finland will soon be the first country in the world to start geological disposal of spent nuclear fuel, as Posiva Oy begins operations in the coming years [1]. Many nuclear safeguards issues have been tackled to allow the reliable and robust verification of all the spent fuel items to be disposed of. The main challenge with geological disposal is that the fuel becomes practically inaccessible after disposal, and thus all required information about the fuel needs to be gathered beforehand.

2 METHODS

The Finnish support programme to the IAEA (International Atomic Energy Agency) has been active in developing Non-Destructive Assay (NDA) methods for spent fuel verification for decades. The development work has led to the realisation of the PGET device (Passive Gamma Emission Tomography) and its approval for operative use by the IAEA in 2017 [2]. In addition, STUK has developed its own version of fissile content detection, the PNAR device (Passive Neutron Albedo Reactivity), which will complement the PGET device in final disposal measurements.

2.1 Passive Gamma Emission Tomography (PGET)

The PGET device is shaped as a large torus with a 33-centimeter central hole. Two highly collimated detector banks with 91 CdZnTe semiconductor detectors each are located on either side of the torus. The detectors rotate a full 360-degree spin around the fuel and gather gamma data from all angles, in four adjustable gamma energy windows [3]. A two-dimensional cross section of the fuel can then be reconstructed using a dedicated iterative algorithm. The reconstructed gamma intensity image allows a rod-level detection of anomalies in the fuel assembly. An illustration of the PGET device is shown in Figure 1.

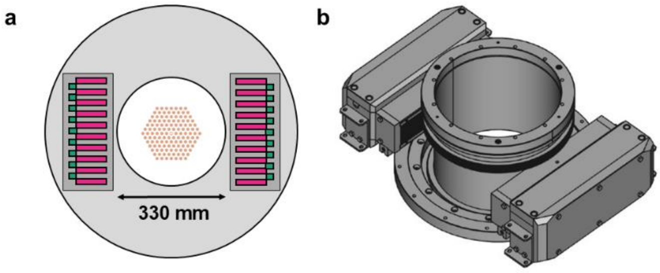

Figure 1: PGET device. **a** A schematic view from the top. Collimators in pink, detectors in green and fuel in orange **b** Device structure without outer cover.

2.2 Passive Neutron Albedo Reactivity (PNAR)

The PNAR device consists of four pairs of gamma and neutron detectors sensitive to fast neutrons that are situated evenly around a central opening, where the measured fuel assembly is placed for measurements [4]. Figure 2 illustrates the PNAR device.

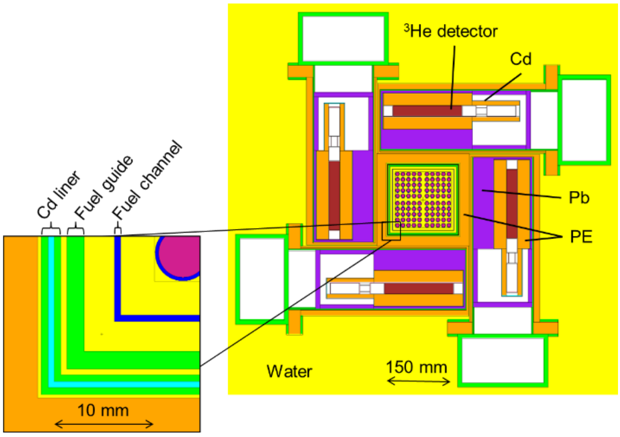

Figure 2: Cross section of the PNAR device.

The neutron flux of the fuel assembly is measured in two different neutron multiplying conditions. First, neutrons escaping the fuel assembly are allowed to be slowed down and reflected back into the fuel from the water and polyethylene surrounding the assembly (i.e. neutron albedo). The thermalized neutrons then induce more fissions and contribute to the detected neutron flux. Second, a suppressed neutron multiplying state is achieved by suppressing the neutron albedo with a cadmium shield that is slid between the fuel and the reflecting materials and detectors. Cadmium absorbs most of the thermal neutrons and thus prevents neutrons thermalized outside the assembly from re-entering it and inducing more fissions. The detected fast neutron ratio of these two states is called the PNAR ratio, and it is a measurement of the neutron multiplication of the fuel. Measuring multiplication allows for direct assay of the fissile content of spent nuclear fuel.

2.3 The combined safeguards approach

Together these two methods, PGET and PNAR, provide a highly reliable verification of the content of the spent nuclear fuel. The two devices will be mounted on top of each other and the measurements will be conducted simultaneously under water in the interim storage of spent nuclear fuel. Figure 3 shows the measurement rack.

Figure 3: The combined PGET-PNAR measurement rack. Left: Lifting of the rack into the pool at the spent fuel storage. Right: Measurements ongoing in the pool. Photos: TVO

In case of loss of Continuity of Knowledge (CoK) during transportation, a PGET device can also be used in the Encapsulation plant for reverification. This option might also be chosen for future verification of fuel from the Loviisa Nuclear power plant, where the transport is significantly longer.

Extensive development work has been done to both these verification methods during recent years. Table 1 summarizes the field measurement campaigns held over the last nine years.

Table 1 Spent nuclear fuel verification campaigns in Finland between 2017-2025 and measured fuel characteristics.

Individual fuel assemblies	155
Initial enrichment range	1.9. – 4.4 %
Average burnup range	5.7 – 56 GWd/tU
Cooling time range	1.9 – 42 years
Campaigns at Olkiluoto nuclear power plant (year)	2017, 2019, 2021, 2022, 2023, 2024, 2025
Campaigns at Loviisa nuclear power plant (year)	2017, 2018, 2020, 2021, 2023

3 RESULTS

3.1 PGET reconstruction quality

The reconstructed image from PGET data shows rod-level gamma activity distribution in the fuel but can also reveal intra-rod differences [5]. Figure 4 shows reconstructed images of the fuel.

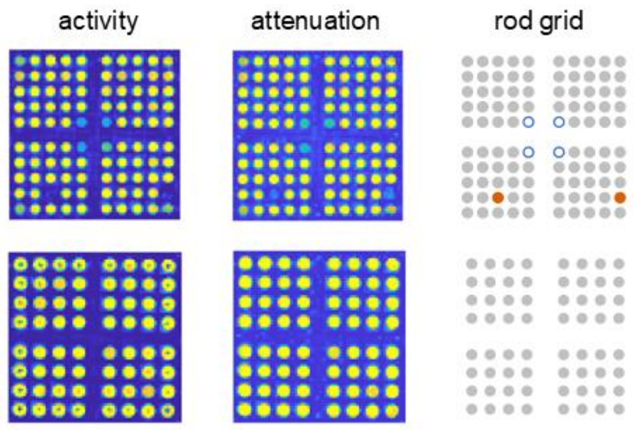

Figure 4: Activity and attenuation reconstructions and the rod grid for two spent nuclear fuel assemblies. Top row: four water channel positions (blue) and two missing rods (red). Bottom: the activity image shows intra-rod activity distribution.

Although the spent fuel is a very strong gamma emitter, the uranium oxide also highly attenuates radiation. In the Finnish case of spent nuclear fuel disposal, all measured fuel will be at least 20 years cooled after use, and in some cases up to 40 years cooled. This means that the initially wide range of gamma-emitting isotopes has been narrowed to a couple of isotopes present in the fuel. Of these, Cs-137 is the most prominent with a half-life of 30 years and a gamma energy peak at 662 keV. Other possibilities are Cs-134 and Eu-154, but these have significantly lower half-lives. The 662 keV gamma peak of Cs-137 is mostly lost in the fuel grid due to attenuation, and this is a challenge that has been addressed in the development of this method [6].

The gamma energy windows for data acquisition are set to optimally capture the Cs-137 energy peak and to ensure that the gathered data gives the best directional information about the fuel. For some 20-years-cooled assemblies the Eu-154 gamma energy peak at 1274 keV has also been tested with promising results, even if this isotope only has a half-life of 8.6 years [6]. Figure 5 shows a typical gamma energy spectrum from two spent fuel assemblies of different cooling time.

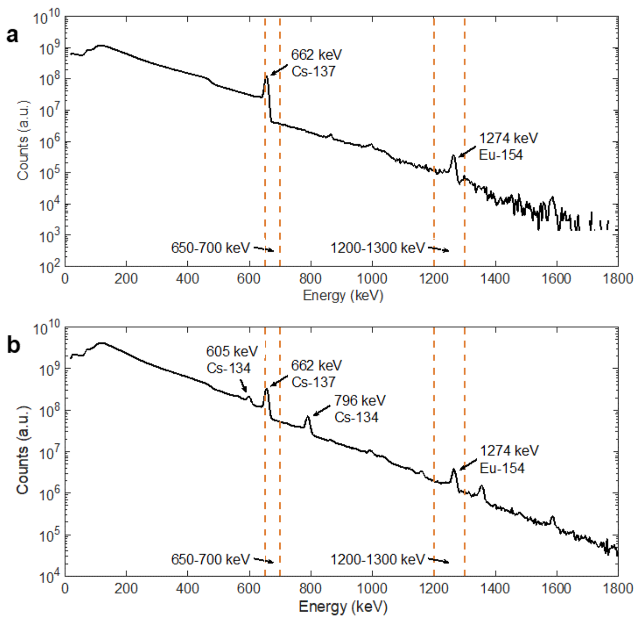

Figure 5: Gamma energy spectra. Dashed lines denote the data acquisition windows (650-700 keV for Cs-137 and 1200-1300 keV for Eu-154). **a** A long-cooled assembly (29 years). **b** A short-cooled assembly (7.2 years).

In case of verification of the fuel at the encapsulation plant, the measurement would take place in air. The ability of the PGET device to function without the shielding effects of the pool water has been investigated during the development of the method. The studies show that the method functions well also with air as medium [7]. The PNAR should in that case be replaced by a standard FORK detector, or further developed to substitute the albedo effect of the surrounding water, e.g. with polyethylene.

3.2 PNAR results

Figure 6 shows the PNAR ratios of all measured spent fuel assemblies between 2019 and 2023 plotted against assembly burnup and initial enrichment. Regardless of original enrichment, the vast majority of spent nuclear fuel has similar leftover reactivity, as the operator has thrived to use the fuel as efficiently as possible within its safety margins. This has resulted into PNAR ratios between 1.03 and 1.05. The bottom of the figure (PNAR ratio = 0.97) presents the theoretical PNAR ratio of a non-multiplying assembly. Error bars are not plotted, but ±1 σ uncertainty approximately corresponds to the marker size.

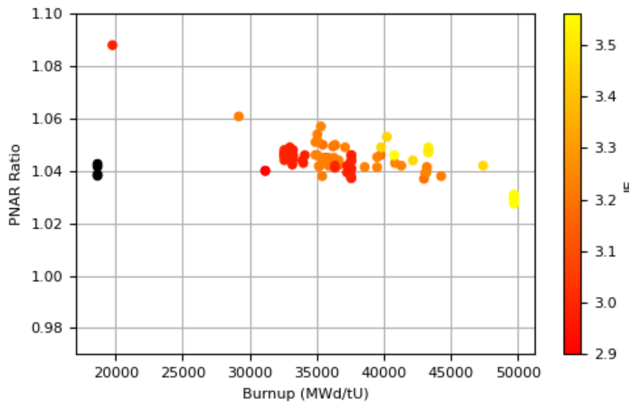

Figure 6: PNAR ratios of all assemblies measured prior to 2024 compared against initial enrichment (colorbar) and assembly burnup. The lower Y-axis limit (0.97) is the theoretical PNAR ratio of non-multiplying fuel.

4 CONCLUSIONS

At the approaching start of operations of the geological disposal facility for spent nuclear fuel in Finland, STUK has refined its non-destructive assay methods for verifying the fuel. The nuclear safeguards concept of the facility relies on the studied gamma and neutron methods, which provide a reliable safeguards verification of the spent fuel.

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