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Comparison of in-air and in-water performance of Passive Gamma Emission Tomography with activated Co rods

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Abstract

With the operations at the geological repository in Finland starting soon, efficient non-destructive assay methods are needed to verify the spent nuclear fuel prior to disposal. Passive Gamma Emission Tomography (PGET) is a method that allows for fuel rod level inspection of the nuclear fuel integrity. Together with the Passive Neutron Albedo Reactivity (PNAR) method, both the gamma activity as well as the reactivity of the spent fuel can be assayed with high confidence. This is essential to make reliable nuclear safeguards conclusions before the fuel becomes inaccessible after the disposal in the geological repository. The PGET method has been developed to be used underwater in spent nuclear fuel storage ponds, but at the spent nuclear fuel encapsulation plant in Finland, there will be the possibility to conduct measurements in a hot cell in air. This has not been tested previously with the device. During June 2022, mockup tests with irradiated cobalt mockup fuel rods were conducted at the Atominstitut in Vienna to investigate the method's performance in air. Five different configurations of mockup assemblies with activated cobalt rods, steel rods and empty positions were measured with the PGET device both in water and in air. The results show that the device performance is similar in both media. Future investigation topics include simulation studies of the effect of the background radiation originating from the parts of the fuel outside of the imaging field of view, and simulation of the scattering of gamma rays from the surrounding hot cell. Test measurements with real spent nuclear fuel are also required to study some effects that could not be verified with the mockup setup, due to the different attenuation and gamma energies of the cobalt rods compared to the uranium and radioactive elements in the spent fuel.

Introduction

As the first country in the world, Finland will soon be starting operations in the geological repository for spent nuclear fuel. The disposal facility is currently being built in Olkiluoto, Eurajoki, and consists of a repository excavated around 400 meters below ground and an encapsulation plant above the ground surface. All spent fuel will need to be carefully verified prior to disposal to make sure that the nuclear material is as declared. Two complementary non-destructive assay methods are used for the verification measurements, namely Passive Gamma Emission Tomography (PGET) [1] to get a pin-level view of the fuel, and Passive Neutron Albedo Reactivity (PNAR) [2] to assay the fissile material content of the fuel.

At the encapsulation plant, there will be a possibility to measure spent fuel in air. The PGET device has never been tested under such circumstances but has only been operated underwater. The aim of this study is to investigate the performance of the method with air as the measurement medium.

The results presented here are a summary of a wider research article that has recently been submitted elsewhere [3]. For a more detailed analysis and a wider range of presented results, please refer to that publication.

Materials and methods

Non-destructive assay methods are needed to verify the spent nuclear fuel prior to disposal. Passive Gamma Emission Tomography (PGET) is an IAEA-approved method for fuel verification, used regularly in inspections around the world. The PGET device consists of two highly collimated CdZnTe gamma detector banks which are housed inside a torus-shaped cover on opposite sides. The collimators allow each of the 182 detectors to see an axially tapered and transaxially very narrow view of the spent nuclear fuel assembly, which is placed in the central opening of the device. During data acquisition, the gamma detector banks are rotated 360 degrees around the fuel assembly and gamma emission data are gathered from all angles. [4-8]

The measured setups consist of different arrangements of activated cobalt rods with a diameter of 7 mm and a height of 10 cm. The rods were assembled in a hexagonal manner, representing the geometry of a real VVER-440 fuel assembly. For some of the measured setups, some rod positions were left empty or filled with inactive steel rods. Figure 1 illustrates three different measurement grids.

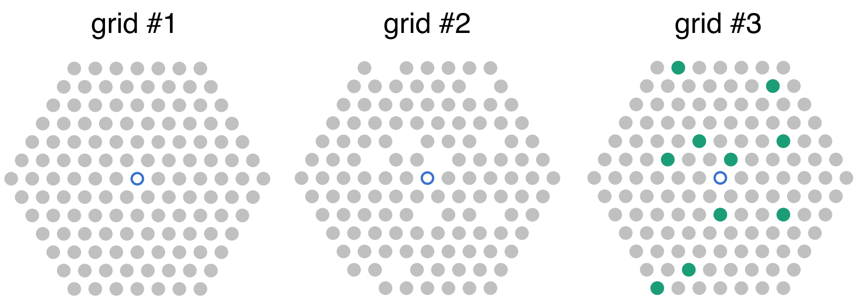

Figure 1 Measured grids. Grey circles denote active cobalt rods, green circles denote inactive steel rods and blue circles denote the central water channel.

All measurements were conducted in a shallow pool of water where the PGET device rests at the bottom. Figure 2 illustrates the custom-built setup featuring a polyethylene pipe that was placed in the central hole of the PGET device, extending above the water surface. For the air measurements, the tube was kept dry, and for the baseline water measurements, the tube was filled with water so that the measured object was fully submerged.

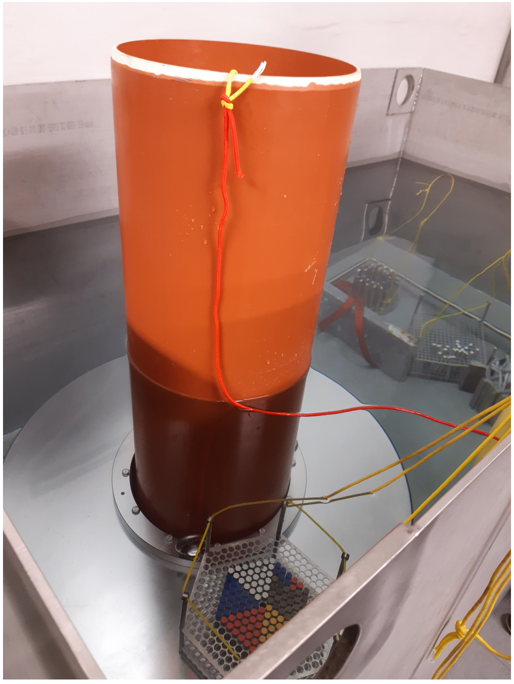

Figure 2 Experimental setup for measurements in air and in water. The tube placed in the central hole of the PGET device was either empty or filled with water. The cobalt rod grid is resting on top of the PGET housing at the front of the image, waiting to be placed inside the tube for measurements.

Usually, the measurements of spent nuclear fuel last around 5 minutes. For the measurements of activated cobalt rods, the much lower gamma activity of the rods requires the data acquisition to last more than six hours per measurement. Most of the measurements were conducted so that the device stopped for 62422 ms for each of the 360 measurement angles, allowing for sufficient counting statistics to be recorded.

Based on the gamma emission data gathered, 2D cross-sectional images of the object can be reconstructed by using software specifically tailored to this purpose. The ill-posed inverse problem is formulated as a constrained minimization problem and solved with an iterative scheme that calculates the activity and attenuation images of the object simultaneously. The mathematical approach is explained in more detail in [9].

The image quality index is a quantitative measure developed to compare how well the empty and filled rod positions in the grid are separated from each other. This value helps in determining the ability of the method to identify possible missing rods. The index consists of two values (Δ, σ_f): Δ describes how well the average activities of empty or modified positions in the grid are separated from the average activities of the filled grid positions. It is defined as

$\Delta = (\mu_f - \sigma_f) - (\mu_e + \sigma_e)$, where μ_f and μ_e are the activity means of filled and empty grid positions, respectively, and σ_f and σ_e are the standard deviations of the activities of the filled and empty positions, respectively.

Results and discussion

Comparison of results from the energy windows with the Compton edge and the photopeak

Data were acquired in two different gamma energy windows, capturing the main photopeaks of Co-60 (at 1173 keV and 1333 keV) and the edges of the Compton continuum (at around 963 keV and 1117 keV). The results were compared in terms of how well the modified grid positions are identified from the images.

Due to the low counting statistics of the measurements, the results of identical back-to-back measurements vary quite a lot. The effect of the poor statistics is illustrated also with images reconstructed from summed-up data of two consecutive measurements. The image quality of such reconstructions is almost always significantly better than the image quality of those two measurements separately.

The results from the gamma energy window of 900-1100 keV capturing the Compton edges seem to be better overall than those from the higher gamma energy window of 1100-3000 keV that captures the photopeaks of Co-60. The image qualities in terms of Δ/σ_f for the 900-1100 keV window are around 8-10, whereas for the 1100-3000 keV the values of Δ/σ_f are around 5-7. A higher value indicates a better separation between the modified rod positions and positions filled with activated rods.

Comparison of in-air and in-water performance

The performance of the method in different measurement media was compared by visually evaluating the images reconstructed from data acquired in air or in water, and by comparing the image quality indices computed from these images.

Figure 3 shows the reconstructed activity and attenuation images for two different grid layouts, both in air as well as in water. For grid #3, the grid positions substituted with inactive steel rods are clearly empty in the activity image but represent filled grid positions in the attenuation image, as they should. For grid #2, both images show the empty rod positions clearly. There are no notable differences between air and water as measurement media.

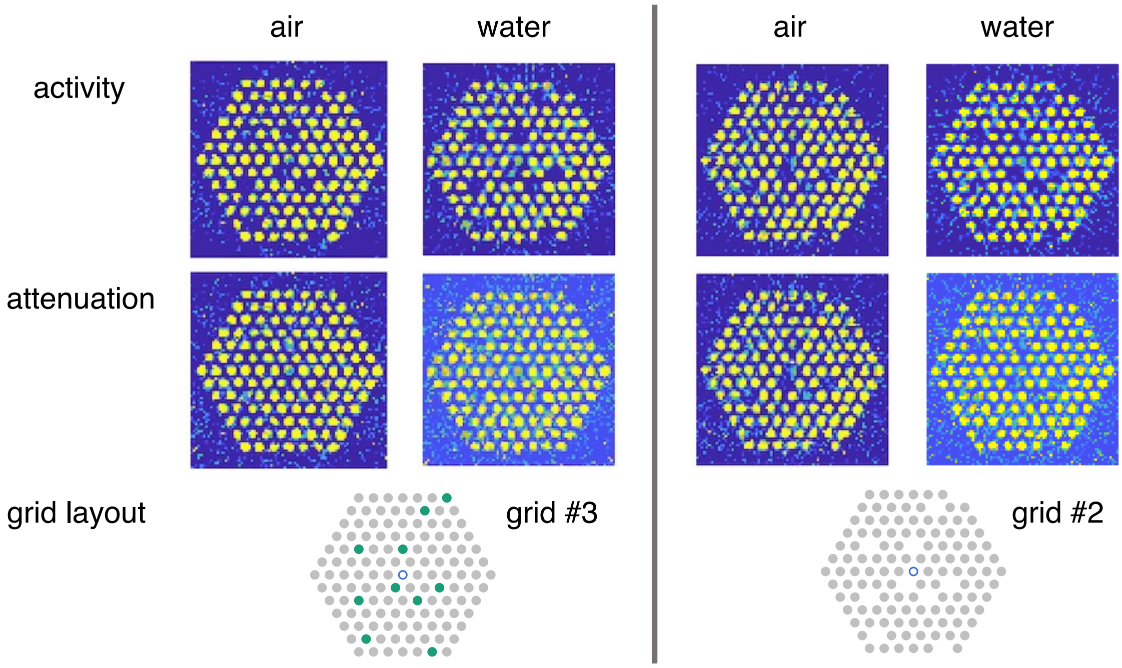

Figure 3 Reconstructed activity and attenuation images for measurement grids #3 and #2, both in air and water. The ground truth geometries are shown below both image sets. The images are reconstructed from data gathered in the gamma energy window 900-1100 keV.

In terms of image quality, the results from the measurements conducted in water seem to show a bit better separation of the modified and filled rod positions. For the water measurements, the image quality in terms of Δ/σ_f is around 8-10, whereas for the air measurements it is usually around 5-8.

Overall, all the reconstructed images show image quality values of more than 5 in terms of Δ/σ_f. This means that regardless of the measurement medium or gamma energy window, the modified grid positions can easily be distinguished from the filled positions.

Conclusions

The performance of the PGET method in air was tested by measuring activated Co-60 rods both in air as well as in water. The method was demonstrated to function well, and no significant effects were observed to be caused by the measurement medium. However, there are significant differences in gamma energies of the studied Co-60 and the prominent gamma emitter isotope Cs-137 present in spent nuclear fuel, and the attenuation coefficients of cobalt and uranium oxide differ quite a lot. Thus, the results from this investigation cannot be directly applied to measurements of real spent nuclear fuel. The effect of the rest of the fuel assembly extending above and below the measurement plane could not be investigated with this setup, either. To assess these issues, simulations of the experimental geometry are being done, and measurements on real spent nuclear fuel in air will be conducted.

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