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# VERIFYING SPENT NUCLEAR FUEL WITH PASSIVE GAMMA EMISSION TOMOGRAPHY PRIOR TO DISPOSAL IN A GEOLOGICAL REPOSITORY IN FINLAND

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## ABSTRACT

Finland is planning to start the disposal of spent nuclear fuel in a geological repository around 2025, and a reliable verification method for the fuel is needed to ensure that all nuclear fuel corresponds to declarations. The development of analysis software for Passive Gamma Emission Tomography (PGET), an IAEA-approved NDA method, is ongoing between STUK, IAEA, the Helsinki Institute of Physics (HIP) and the Department of Mathematics and Statistics at the University of Helsinki.

The torus-shaped PGET device consists of two linear arrays of collimated CdZnTe detectors and collects gamma emission data from spent nuclear fuel assemblies in underwater measurements. 2D images of the activity and attenuation of the assembly can be simultaneously reconstructed from the data with an iterative reconstruction method. The method has been verified using measurements conducted between 2017-2020 at the Finnish nuclear power plants, imaging fuel assemblies with varying geometry, burnup, cooling time and initial enrichment. Rod-level anomalies and even intra-rod differences in activity can be seen.

Currently the analysis process is being automated, and a graphical user interface is being built to ensure efficient operation. The current classification of fuel rods based on the reconstructed attenuation and activity images separates the rods into present and missing rods, but development is ongoing to include a third category for possibly modified or replaced rods. To overcome the challenge of high self-attenuation in the fuel, the reconstruction process needs to be developed further, possibly with simulated data. We have started to use Serpent2 for detailed simulations of the PGET method. The performance of the analysis software will also be optimized and code execution times brought down.

## INTRODUCTION

A geological repository for disposal of spent nuclear fuel is currently being built at Olkiluoto, Eurajoki in Finland. The repository will be the first of its kind once finished, and the disposal is planned to start in the mid-2020's. For nuclear material safeguards, it is of utmost importance to be able to verify the fuel prior to disposal in a justifiable, efficient manner and to ensure that all nuclear material corresponds to declarations, since the fuel will be inaccessible after the disposal. In 2017, the IAEA approved a new non-destructive assay (NDA) method called Passive Gamma Emission Tomography (PGET) to be used in spent nuclear fuel verification. The PGET method will be used together with Passive Neutron Albedo Reactivity (PNAR) measurements to verify the fuel at the intermediate storage facility in Olkiluoto prior to fuel disposal.

Previous studies of PGET image reconstruction [1], [2] showed a need for improvement in the reconstruction of the images. Thus, we developed an iterative reconstruction method [3] that simultaneously reconstructs the activity and attenuation of the fuel. The method has been tested with measurement data from a wide range of spent nuclear fuel and it has proved to produce high quality images of fuel from the Finnish nuclear power plants.

## PRESENT STATUS

The PGET device has been under development by the IAEA and some of its Member States from the 1980's, and has now reached a commercialized stage after multiple prototypes. In the following we will introduce the current device as well as the nuclear fuel measured at the Finnish nuclear power plants during the years 2017-2020. The reconstruction environment and classification concept for the spent fuel rods is presented along with the current simulation platform used in developing the method further.

### Passive Gamma Emission Tomography

The current version of the commercialized Passive Gamma Emission Tomography (PGET) device consists of 182 detectors arranged in two banks on opposite sides of the torus-shaped device (see Fig. 1, left). A fuel assembly is placed in the middle of the torus and highly collimated CdZnTe gamma detectors are used to gather gamma emission data from all angles around the fuel by rotating the detector banks. Measurements are done underwater in deep storage pools (see Fig. 1, right). The PGET method is able to detect anomalies in the fuel assembly up to a precision of one single fuel rod. A more detailed description of the device can be found in [4].

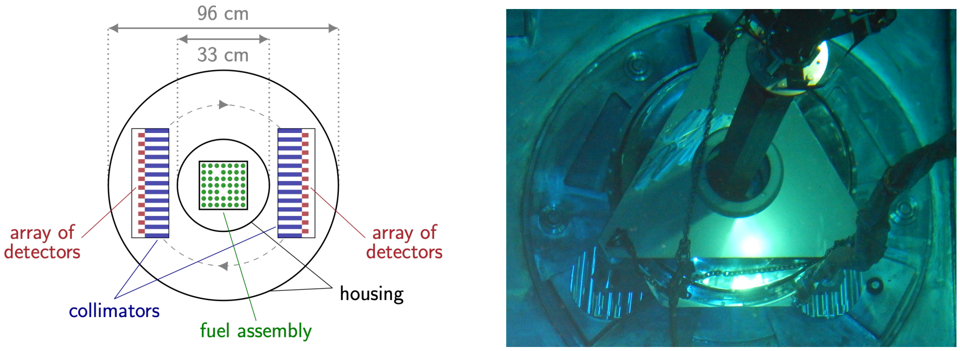

**Figure 1: Left: A schematic transaxial view of the PGET device. Collimators are in blue, detector banks in red and the fuel assembly in green. Right: PGET in underwater measurements in a spent fuel pond at Loviisa NPP in 2020. Photo courtesy of Fortum.**

The device is operated from a measurement computer poolside, and the data collection takes around 5.5 minutes per assembly. The gamma emission rate is collected in four separate energy windows, usually 400-600 keV, 600-700 keV, 700-1500 keV and 1500+ keV. In addition, gamma energy spectra and gross neutron counts are collected for each assembly.

There is an aim to operate the PGET measurements remotely in the future. The process will also be automated so that minimum interference is needed. The remote operation capabilities have already been tested by controlling the measurements from Vienna and Luxembourg in a measurement campaign in 2018.

## Measured nuclear fuel

During the past four years we have measured 78 different fuel assemblies and multiple fuel dummies and pin containers at the Finnish nuclear power plants in Olkiluoto, Eurajoki and Hästholmen, Loviisa. 38 different VVER-440 assemblies have been measured as well as 39 BWR assemblies of 9 different types (8x8-1, 9x9-1AB, ATRIUM10B, GE12, GE14, SVEA-64, SVEA-100, SVEA-96 OPTIMA and SVEA-96 OPTIMA2). The burnups of the measured fuel have varied between 5.72 and 55.0 GWd/tU, the cooling times between 1.87 and 34.6 years and the initial enrichments between 1.9 and 4.4 %. Among the measured fuel there have been eight assemblies with missing fuel rods or rods that have been in the reactor core for a shorter time than the rest of the rods. Included are also several assemblies with burnable absorber rods.

## Reconstruction environment

Our iterative reconstruction algorithm [3] reconstructs images of both the activity and attenuation of the measured fuel simultaneously. The simultaneous reconstruction problem is inherently challenging (being non-linear and ill-posed), but ignoring the benefits of estimating also the attenuation map would provide poor results in our case of a very highly self-attenuating object. Thus, by using a priori information about the location and dimensions of fuel rods inside the fuel assembly, the problem can be regularized. The reconstruction problem is formulated as a constrained minimization problem and solved with a Levenberg-Marquardt type of algorithm. The presence of fuel rods is not assumed inside the known fuel grid, but a rod position is only assumed to have the shape of an homogeneous circular object, be that water, fuel or some other material. We apply a minor constraint on the attenuation-activity combinations that are accepted. By doing this we do not assume too much from the object under reconstruction and do not unnecessarily steer the process towards certain outcomes.

The method has been tested with a wide range of spent nuclear fuel from the Finnish power plants with satisfying results [5]. A single missing spent fuel rod can be detected and even intra-rod activity differences are visible in reconstructions from certain types of fuel.

## Fuel rod classification

The current classification of fuel rods is based on a support vector machine (SVM) trained on data from the IAEA, both from mockup fuel assemblies measured at the ATI in Vienna and from real nuclear fuel. The classification is done on a plane where the individual rod positions are depicted as points of average activity. The x-axis is the rod's activity difference from its nearest neighbors and the y-axis is the rod's distance from the assembly center. All rod positions falling on the left side of the classification line will be classified missing and the positions on the right will be classified present. A typical classification plot is shown in Fig. 2 on the right, and a schematic of the fuel assembly is illustrated on the left.

An index for water channel detection is used to compare the visibility of the central water channel in VVER-440 fuel assemblies. The index is calculated from values in the same classification plan as shown in Fig. 2. The absolute distance between the water channel and the mean of all present fuel rods is divided by the standard deviation of the present rods. These ratios represent the ability to distinguish the water channel from the rest of the rods, and typically values above 3 give an indication of a good separation between the groups.

## Serpent 2 simulations

The Serpent 2 Monte Carlo particle transport code is a three-dimensional, continuous-energy simulation tool developed by the Technical Research Center of Finland (VTT) for use in reactor calculations [6]. Recently the code was updated with a photon transport model [7] that allows tracking of photons inside the simulation geometry.

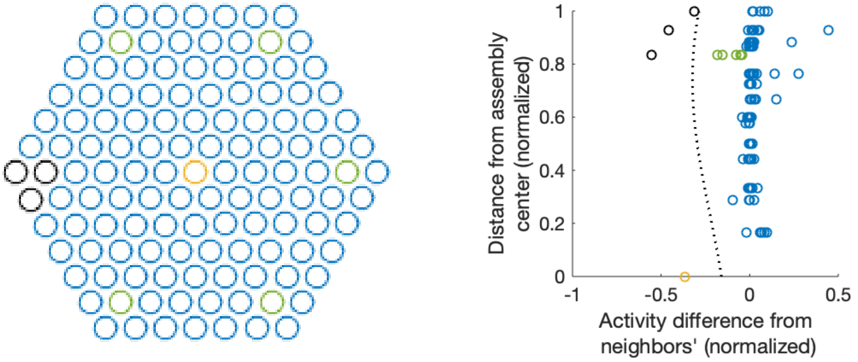

**Figure 2: Left: A schematic of a VVER-440 assembly with three missing rods (black), five burnable absorber rods (green) and a central water channel (yellow). Right: A rod classification plot for the same assembly. Rod activity difference from the nearest neighbors as a function of the distance from the assembly center. Circles represent individual rods and colors denote ground truth rod type (blue for present, yellow for water channel, green for burnable absorber rod and black for missing rod).**

The Serpent 2 environment has been used to simulate the gamma emission arriving at the detectors of the PGET device. An accurate physical model of the PGET device was used as the geometry for the simulations. VVER-440 fuel assemblies have been simulated, both with uniform initial burnup and with cases of missing rods in the central parts of the fuel.

The process starts with an initial phase where a desired fuel assembly is simulated with a burnup calculation. This data is then used as input for the second phase, where the nuclide inventory of the assembly is calculated after a certain cool-down period. In the final part of the simulation, which is specific to the PGET device, the simulated assembly is used as a gamma emission source in the photon transport calculations performed in the PGET geometry.

## FUTURE IMPLEMENTATION

In the following we will briefly introduce our upcoming development projects. We are aiming to improve the reliability of the classification, to develop the method further with the help of simulations, and to optimize the visibility of possible missing or substituted rods in the created reconstructions by choosing the projection angles wisely. All development is focused on making the method more suitable for spent nuclear fuel verification prior to spent fuel disposal in a geological repository.

### Third category for classification

The current classification scheme only classifies the fuel rods into present and missing ones. There are, however, situations in which a rod might fall in between these categories, for example if only a part of the rod is missing or if the fuel rod is substituted with a rod of similar dimensions but of another material. The substitute material might even be activated to make detection harder.

The PGET device's field of view is around 20 cm in the vertical direction due to the conical collimators. Thus, if the edge of a partly removed fuel rod is inside the field of view, only part of the rod is visible and brings the measured activity down. The rod might seem to be missing even if that is not the case.

For these kinds of situations we are planning to include a third classification category into our classification method, a category of "possibly modified" rods. While the occurrence of an undeclared missing rod is automatically an alarm, the presence of a "possibly modified" rod would indicate a need for further investigation. The measurements could then be repeated or other available methods could be used to investigate if some nuclear material indeed is missing, or if the situation is acceptable, for example due to the declared presence of burnable absorber in the rods.

The current classification method based on SVMs does not easily convert from two categories into including also a third one. There is, however, a possibility to include a "grey" zone of unclear objects as bands around the current classification border. Every rod position falling inside this grey band would be classified as possibly modified and would need further investigation.

Another way to classify the rods into three categories would be to use a different classification platform altogether. For example machine learning approaches could be utilized to have any number of categories.

## New classification method of baseline activities

A large issue with the current classification algorithm is that in order to train the support vector machines that provide the classification border, we need good quality training data from similar assemblies that will be analyzed. We currently have a somewhat extensive library of different assemblies of varying burnups, cooling times and types, but only a small fraction of these assemblies contains rod positions with missing or replaced rods. Therefore, our data lacks cases to train the algorithm to notice positions where rods are missing.

To solve this problem, an idea of a baseline activity library for present rod positions was introduced. Because we do have extensive amounts of data from very typical assemblies of different types, where all of the rods are in place as they should, we could develop a library of average activities for present rod positions. Most of the assembly types have a symmetry that could further be utilized to get even more rod positions to each subcategory of rods.

Each individual, differing rod position would be taken from all assemblies of that type and a baseline activity average would be calculated for that position. By doing this to each rod position in the assembly, we could come up with a very typical, characteristic baseline assembly where each rod position would have an average activity value. The baseline values would also need to be normalized to the assembly burnup and cooling time to take into account the effect of these parameters on the absolute values of activity. New measured assemblies could then be compared to this baseline assembly, rod position by rod position, and a deviation from the baseline activity would then be classified as a possible missing fuel rod. The idea of baseline activity classification is presented in Fig. 3 with a simplified example of a 4x4 fuel assembly.

By using this method of baseline activities we could utilize our vast data bank of assemblies with no unusual missing rods to our advantage. A fuel rod position with a missing rod would show a significantly lower average activity value compared to the baseline for that rod position.

We do not currently have enough training data from all assembly types, but for most of them there are enough measurements to get a reliable activity baseline. Assembly symmetries can also be used to our advantage: in square fuel there are often 4 quarters of similar rod positions in the assembly and similarly with hexagonal fuel, the symmetry is sixfold. For some BWR fuel assembly types the symmetry might be reduced to two due to control rod positioning. The control rod crosses are in the same horizontal position with respect to their supercell (containing four fuel assemblies) throughout their lifetime in the core. Thus two sides of each assembly are always near the control rod and two sides always further away, creating a possible burnup gradient inside the assembly.

## Serpent simulations in developing the method

Simulation tools are crucial in understanding the physical phenomena at play inside the fuel assembly. They can be used to improve the accuracy of the reconstruction model and to gain more data for the development of the method.

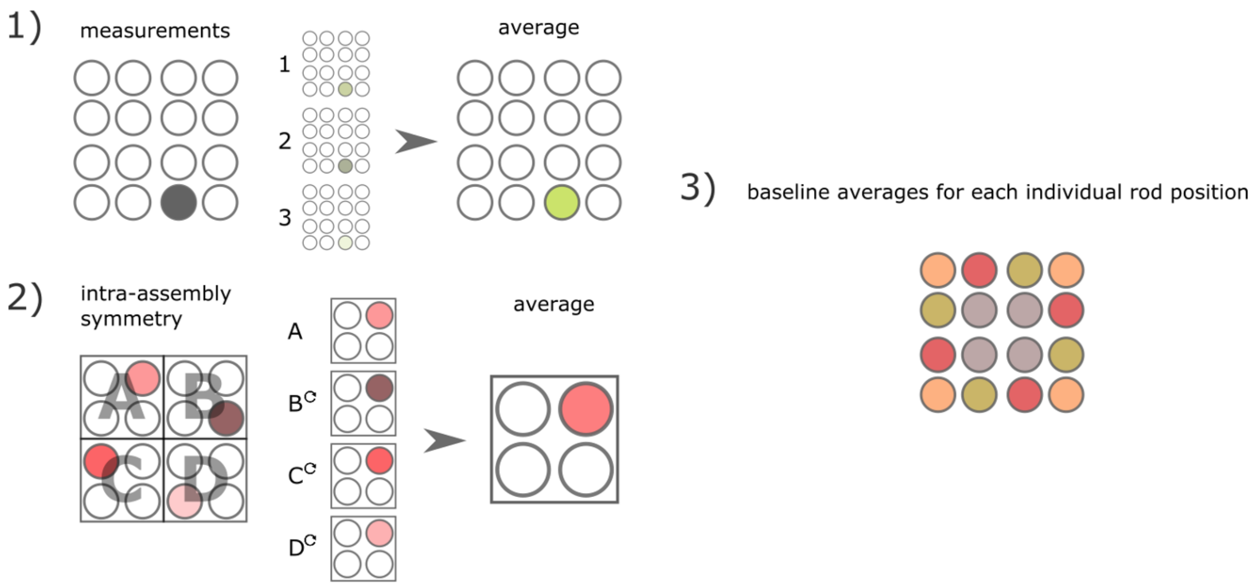

**Figure 3: A simplified explanation of the proposed new classification method. 1) An average activity for a certain rod position is gained from multiple measurements (1-3) of the same assembly type. 2) Intra-assembly symmetry (A-D) is used to get an average activity for each rod position inside the base cell. Parts B-D are rotated to be in the same position as A. 3) Both of the previous averages contribute to the baseline activity averages for each individual rod position (in this simplified case 3 measurements and a fourfold symmetry means that each position is an average of 12 data points).**

With simulations it is possible to study scenarios from which we otherwise lack measured data. Measurement campaigns with real used nuclear fuel are rare and costly, so simulations complement the measurements well. For example, cases with removed rods near the central parts of the assembly are non-existent in the pool of available assemblies that we could measure. With simulations, such scenarios are readily implemented.

Understanding the phenomena inside the fuel assembly, for example how the gamma emission is scattered inside the fuel grid, is very valuable in developing the method further. Simulations could also be used as training data for the machine learning algorithms doing the classification of the fuel.

Our next goal is to study scattering phenomena inside the fuel. At the moment the model assumes perfect detectors and does not include detector response, but we are in the process of expanding the model further. Simulation results could guide the focus of improvements in the forward model: understanding which phenomena are important to model as accurately as possible and which phenomena do not contribute as much to the result.

### Projection angle optimization

The quality of the reconstructions was further improved by the optimal choice of projections from the available 360 different angles. Our studies show that using all 360 projections does not always produce the best images in terms of detecting possible missing fuel rods. The computational demand also grows as more projections are introduced. Thus, we investigated how the projection angles should be chosen to get the best results with minimal number of projections.

Our previous studies [8] had shown that the angles at which the detector sees straight through the assembly from in-between the fuel rod rows or columns are essential to the image quality. There are six of these "see-through angles" in a hexagonal fuel assembly and four of them in a square assembly. The idea of the see-through angle is illustrated in Fig. 4, where some of the ray views through the fuel assembly are shown on the left. The sums of all counts per detector are shown on the right, illustrating how the count rates are lower when the detector sees the empty space between the rod columns and higher when the full column is in view.

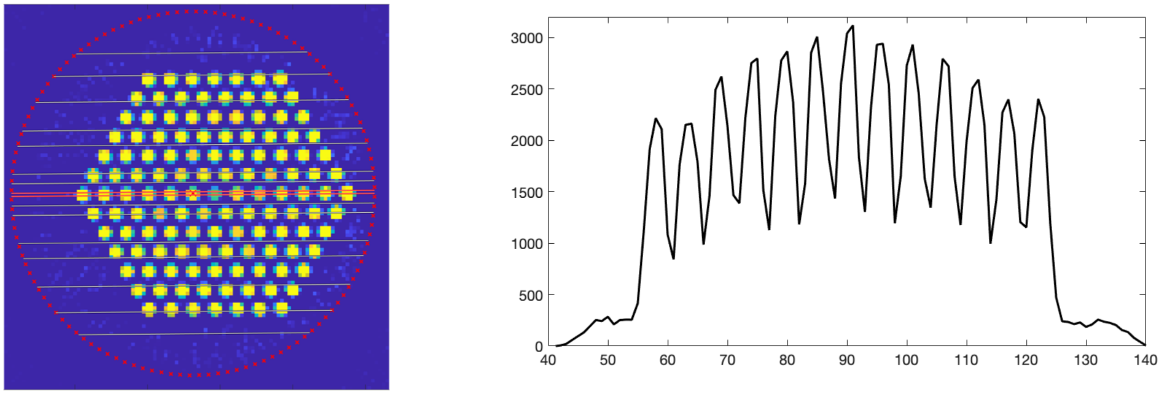

**Figure 4: Left: Detector ray views for projection around angle 90 on top of an activity reconstruction of a VVER-440 assembly. Right: sums of all counts per detector (x-axis) for projection at angle 90.**

There are several ways to choose the 120 or 90 uniformly distributed projections used in the reconstruction, 3 for the 120 projection case and 4 for the 90 projection case. We studied how including the see-through directions among the projections affected the reconstruction quality by using different schemes to pick the 90 or 120 angles used in the reconstruction.

The effect of different projection choice schemes on the reconstruction is shown in Fig. 5 for a VVER-440 assembly. With the 120_1 and 120_3 schemes all of the see-through angles are included in the projection set, and with the 120_2 scheme none of them are. The indexes of water channel detection (as explained in Section "Fuel rod classification") are 16.5, 13.0 and 14.6 for each of the schemes, respectively. The index describes how well the water channel is separated from the rest of the fuel rods and allows comparison between different projection schemes. Although the indexes are high for all of the three cases, the 120_2 scheme shows the worst separation of the water channel.

The reason why the see-through angles prove to be so powerful in delivering quality to the reconstruction were clarified a bit by using the measurement forward model to simulate a single emitting fuel rod inside a full grid of attenuating fuel rods. Fig. 6 shows a simulated fuel rod in both the central part of the grid as well as at the outer edge. On the right, the resulting sinograms show the characteristic behaviour caused by the high attenuation of the fuel rods inside the grid. The sinograms show an increase in the activity values each time right before and right after the single emitting fuel rod is blocked from the detectors by the other fuel rods. This short gap of clear view to the insides of the fuel assembly allows for gamma counts from inside to reach the detectors, despite the high attenuation of the rods in the grid.

### Partial rod edge detection

Our previous studies [5] showed some activity decrease in the corner rods of a certain type of assemblies. Further investigation has shown that this particular fuel assembly type has additional partial rods at the outer corners of the grid, and our measurement data was gathered at a position where the partial rod was only partially in the measurement device's field of view. Thus the results are in line with what we know about the assembly and give indication that even a partially removed or replaced fuel rod would be detectable, if the measurement height is favourable.

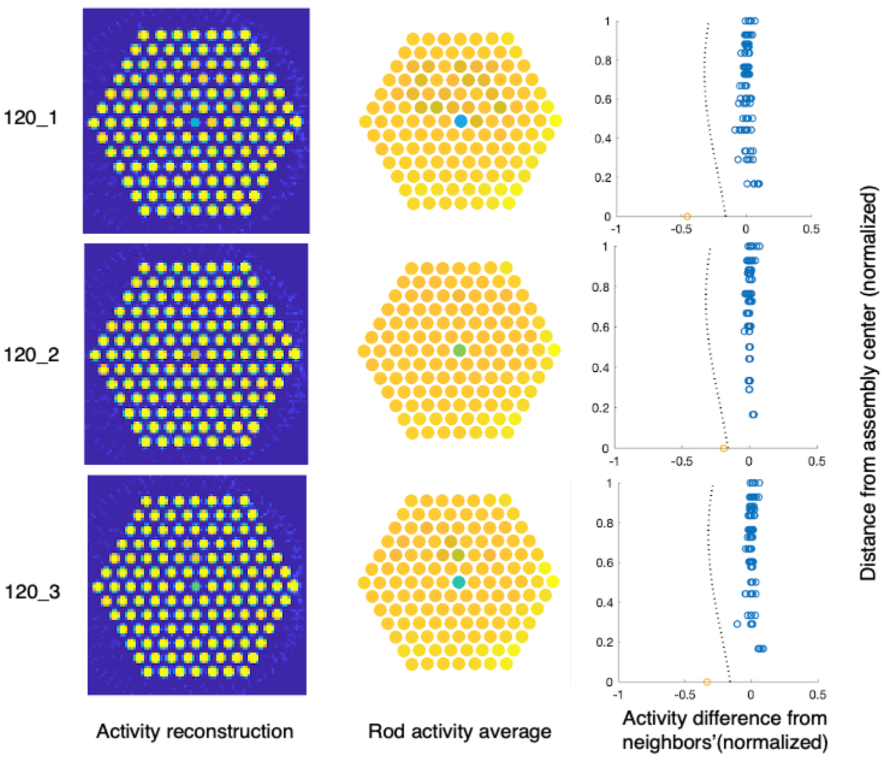

**Figure 5: Projection angle scheme effect on the reconstruction and classification. From top to bottom, 120_1, 120_2 and 120_3 schemes, activity reconstruction on the left and rod activity averages in the middle. On the right, each circle represents a rod position and colors denote ground truth rod type (blue for present and yellow for water channel).**

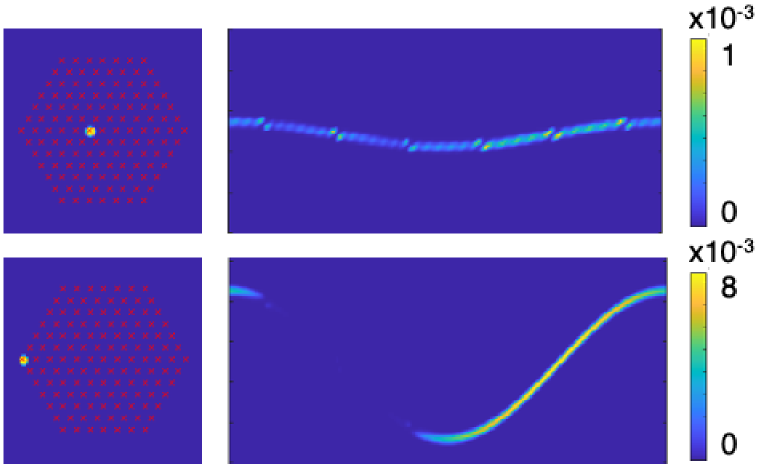

**Figure 6: Simulation of a single emitting rod near the center of the assembly (top row) and near the edge (bottom row). The left column shows the activity maps and the right column the resulting sinograms and the colormaps.**

We are going to further investigate how much of the inactive part of the partial rod needs to be in the field of view of the device in order to notice that something is missing. In summer 2021 we are going to perform further measurements at the Olkiluoto nuclear power plant and do an axial scan around a partial rod end point. This way we can determine with good precision how sensitive the device and reconstruction are with regard to partially missing fuel rods.

### In-air PGET measurements

Up to now, the PGET device has only been used in water in spent fuel storage pools, because no facility for in-air measurements has been available up to now. However, the encapsulation plant that Posiva is building at Olkiluoto, Eurajoki, includes a possibility for PGET-measurements in air at the facility. This option would be used as a last resort if there was some disturbance or uncertainty with the underwater measurement or if the continuity of knowledge needs to be re-established.

Using the device in air poses several challenges that need to be overcome for the device to function as planned. First of all, water has acted as a shield to the detectors and reduced the amount of background radiation coming to the detectors from above or below. The spent fuel assembly is highly active and all gamma counts to the detectors that do not originate from the field of view of the device worsen the real signal.

When the device is used in air at the encapsulation plant, additional shielding must be built around the detectors, because the collimators do not shield well enough from radiation coming from above, below or even from the backside of the detectors. The full system including the measurement device and the shielding also needs to be below certain weight limits for suspension from the ceiling of the measurement chamber to be possible.

There are plans to model and simulate the measurement environment to help with the design of the shielding. The space is so tight that scattering of the gamma rays from the walls, floor and ceiling need to be taken into account as well. Different material choices for the shielding part itself need to be considered. In our case lead might come into question since the weight limits are not so strict and lead will be more cost-effective than for example tungsten. If the encapsulation plant measurements prove to be reliable, there is an option to move the verification completely to the encapsulation plant in the future, but further development of the method is needed first.

## CONCLUSION

The current PGET reconstruction and classification process is able to detect rod-level anomalies in spent nuclear fuel from a wide range of different types and parameters. These conclusions on missing and present fuel rods are based solely on gamma emission data from spent fuel assemblies and some minor details about the geometry of the measured fuel, available from public references. Still, there is room for improvement with the quality of the reconstructions and thus the classification accuracy. When the disposal of spent fuel begins, the verification system needs to be available for automated, remotely controlled measurements as well as accurate and justifiable conclusions analyzed from the gathered data. The final product also needs to satisfy strict requirements for false alarms to ensure smooth operation of the disposal process. Thus, the development continues to provide the best possible method for verification of spent nuclear fuel prior to disposal in a geological repository in Finland.

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