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3D RECONSTRUCTION OF INNER STRUCTURE OF RADIOACTIVE SAMPLE UTILIZING GAMMA TOMOGRAPHY

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Abstract. *A unique 3D tomography apparatus was built and successfully tested in Research Centre Rez. The apparatus allows a three-dimensional view into the interior of low-dimension radioactive samples with a diameter up to several tens of millimeters giving a better resolution than one cubic millimeter and it is designed to detect domains with different levels of radioactivity. Structural inhomogeneities such as cavities, cracks or regions with different chemical composition can be detected by using this equipment. The SPECT scanner has been successfully tested on several samples composed of a 3mm radionuclide source located eccentrically within homogeneous steel bushings. To detect fine cracks inside small samples an ultrafine scan of the sample was carried out in the course of 24 hours with a 0.5 mm longitudinal and transverse step and 18° angular step. The exact location and orientation of a fine crack artificially formed inside a sample has been detected.*

Key words: *Collimator, convolution filter, Fourier transform, gamma tomography, radioactivity, radon space, scintillation detector*

1. INTRODUCTION

Due to the demand from nuclear industry for extending the lifetime of nuclear power reactors of Generation II by twenty to forty years as well as for high reliability and safety of nuclear reactors of Generation III and IV, a complex characterization of the degradation of materials properties caused by long-term exposition to high doses of neutron radiation in nuclear and thermonuclear reactors is necessary. Another subject of the project is the research and development of advanced technologies and materials in the area of thermonuclear fusion.

Obtaining a comprehensive description of the degradation of structural and mechanical properties of nuclear reactor components after long-term operational exposure helps us evaluate the service life, reliability and safety of nuclear reactors. This includes tests utilized both at room temperature and at elevated temperatures, such as tensile, impact and fracture toughness and crack growth rate during cyclic loading measurements, low-cyclic fatigue and creep tests. These tests are carried out with non-irradiated and highly irradiated material exposed to a high neutron flux for a long time within a reactor core.

The possibility of scanning and subsequent reconstruction of the threedimensional (3D) map of a distribution of the activity within the sample provides further useful information for the overall analysis of degradation of samples exposed to long-term neutron fluxes. For this reason, a unique 3D tomography apparatus measuring the distribution of the activity inside the sample was built and successfully tested in Research Centre Rez [1] – Figure 1. This scanner is based on the Single Photon Emission Computed Tomography (SPECT) [2], which is advantageous due to the possibility of 3D image computing.

The apparatus allows for 3D view into the interior of low-dimension radioactive samples with the diameter up to several tens of millimeters. Structural inhomogeneities such as cavities, cracks or regions with different chemical composition can be detected by using this equipment.

The unique collimator design, the use of stepper motors for fine and accurate sample scanning, along with the advanced 3D image reconstruction software developed at Research Centre Rez, allow for the resolution better than 1 mm^3 to be achieved.

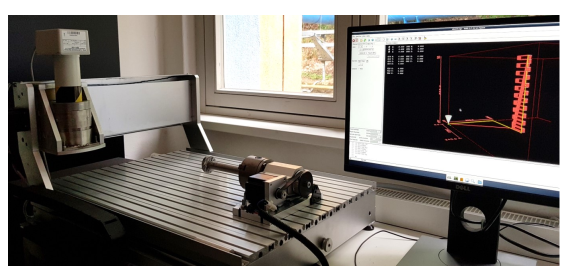

Figure 1. SPECT scanner – real device manufactured by ALVAT company [3]

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Devices working on a similar principle have been used for decades, e.g., in nuclear medicine for the diagnosis of malignant tumors, and are increasingly being applied in the nuclear industry [2]. However, for the first time similar equipment is used for non-destructive testing of low-dimension radioactive samples.

2. Hardware part

The scanner consists of a rotary sample holder and a scanning device to enable scanning across the transverse plane of the sample and moving the detector in the longitudinal direction of the sample.

The detection system consists of an intelligent REP171-ISD scintillation probe controlled by processor, with regulated high voltage source, current / frequency converter, photomultiplier working in current mode, i.e. without dead time. Dynamic response measurement is 5 orders without switching, measurement uncertainty <2%. The scintillation crystal is encapsulated $CdWO_4$, ø10x30 mm, which was selected for ^{60}Co gamma radiation detection efficiency, its length was optimized for full gamma-ray absorption, a small diameter for good signal / background ratio. The crystal is shielded by a steel shielding with a wall thickness of 40 mm.

The $CdWO_4$ scintillation detector with current mode photomultiplier and signal processing unit operating in current mode makes it possible to reach the measuring range of the relative signal current response of at least 5 orders without switching and without dead time.

3. Software part

The development of a specialized 3D image reconstruction software based on a method known as the filtered back projection began in 2015. Initially, the software was created for recording signal timing from the detector and for converting this record into sinograms [4], [5].

The reconstruction method is based on the Fourier central slice theorem led through the origin of the coordinate system, which was firstly used in [6], which states that the 1D Fourier transformation of the object projection taken at a given angle is equal to the 2D Fourier transformation of the object image at the same angle. The SPECT image was filtered by the RAMP filter [7], which linearly emphasizes the individual frequencies, thus, locally suppressing the star artifact [8] arising in the reconstructed image due to the finite beam width and a number of projections of the scanned object.

The 3D reconstruction of the object space from the sinograms was performed by using Python programming language, which allows to obtain a high-quality 3D image [8], [9].

4. Function and implementation: first campaign

In March 2017, when the device was optimally tuned, the 3D scanning was carried out. The SPECT scanner has been successfully tested on several samples consisting of a radionuclide source ^{137}Cs with diameter and height of 3 mm and of 10 MBq activity, eccentrically stored within homogeneous 10 mm thick steel capsule.

The radiation emitted by the sample is collimated by a series of interchangeable tungsten collimators with different diameters and the aperture profiles allow to flexibly optimize the ratio between the resolution and SNR depending on the physical characteristics of the sample.

In order to get 3D information about the whole specimen, several series of measurements in different cross-sections is necessary. For this purpose, further movement of the detector in the longitudinal direction (perpendicular to the transverse plane of the sample) is required. The processed sinograms had the size of 20 x 20 pixels, which corresponds to lateral step size of 0.5 mm. The angular step size was 360°/20 = 18°. Therefore the whole sample is rotated by a fixed angle 18° and the transverse motion of the detector is repeated. The sample is gradually rotated by 360°, thus the general image can be reconstructed.

Each scan (a set of values obtained for one particular sample rotation angle) forms one line of the so-called sinogram – the Fourier image of the scanned slice, in the so-called Radon space (developed by Johan Radon in 1917) [10], [5]. The individual rows (for different angles of sample rotation) then form a matrix of values constituting the entire sinogram. Before the inverse Radon transformation of the Fourier images of the scanned object (sinograms) is made, a low-pass filter convolution was used to eliminate the statistical fluctuations of the signal.

Figure 2 shows a comparison of the original (left) and convolved (right) sinograms. In this case, the convolutional core consists of a 3 x 3 matrix.

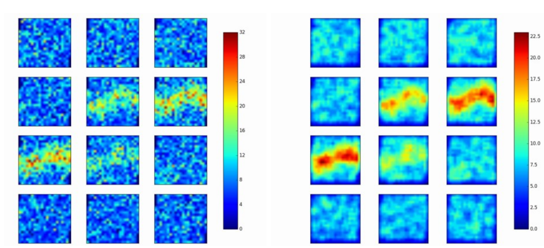

Figure 2. Comparison of measured (left) and filtered (right) sinograms of a small radionuclide source ^{137}Cs, 3 mm in diameter and of 10 MBq activity, eccentrically stored within homogeneous 10 mm thick steel capsule.

4.1. Results

Each of the sinograms carries complete information about the scanned cross section of a sample in the Radon space. To get the 3D information about the whole specimen, several series of measurements in different cross-sections are necessary. For this purpose, further movement of the detector in the longitudinal direction (perpendicular to the transverse plane of the sample) is required. This information can be reconstructed through a number of different mathematical algorithms. In this case, the algebraic iteration method, known as Kaczmarz method [11], and the mathematically more demanding algorithm, known as the filtered back projection, were used [6].

The final 3D image of activity distribution within the sample is obtained by combining the individual tomographic slices. The tomographic 3D reconstruction of the individual scanned samples with a unique identification of the position of the emitter can be seen in Figs. 3 and 4 [12].

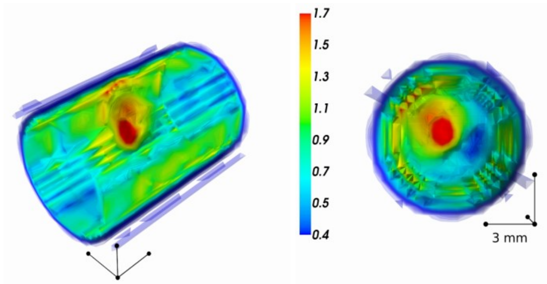

Figure 3. 3D scans of a small radionuclide source ^{137}Cs, 3 mm in diameter and of 10 MBq activity, eccentrically stored within homogeneous 10 mm thick steel capsule, computed by utilizing the Kaczmarz method.

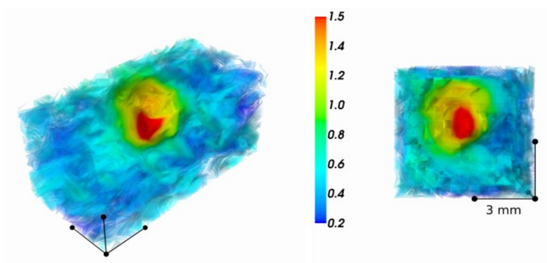

Figure 4. 3D scans of a small radionuclide source ^{137}Cs, 3 mm in diameter and of 10 MBq activity, eccentrically stored within homogeneous 10 mm thick steel capsule, computed by the filtered back projection.

5. Ultrafine scanning campaign

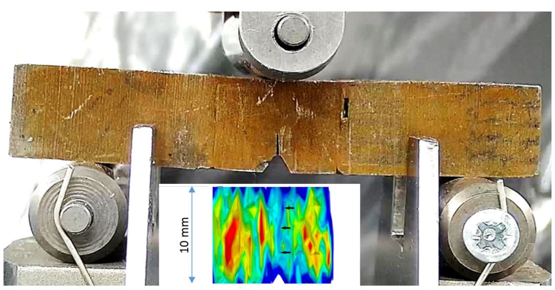

Figure 5. The small sample of activity 1 MBq of ^{60}Co, with the fine crack (about 0.5 mm) artificially formed inside the sample. A colored insert is representing 2D slice of ultrafine 3D scan with a 0.5 mm longitudinal and transverse step and 18 ° angular step. We observe a distinct crack in the shape of a dark blue line roughly at the center of the image, which is indicated by black arrows.

To detect a fine crack (about 0.5 mm) artificially formed inside a small prism (10 x 10 x 20 mm) of activity 1 MBq of ^{60}Co, the ultrafine scan of the sample was carried out with a 0.5 mm longitudinal and transverse step and 18 ° angular step.

The scanning lasted for 26 hours. The results can be seen in Figure 5. The crack is well visible on a 3D scan as a dark blue curve roughly in the middle of the image.

5.1. Collimators

The replacing of the original lead collimator by a set of tungsten collimators ø100 x 50/100 mm, with hole ø 1 and 2 mm or slot 20 x 1 mm, interchangeable according to the type of scanning sample, allowed for a flexible optimization of the ratio between the resolution and SNR depending on the specific physical characteristics of the sample (Figure 6). Calculations of the design solution were implemented in the MCNP (Monte Carlo N-Particle) code [13].

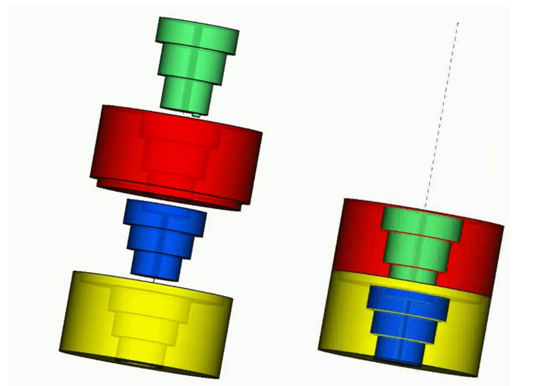

Figure 6. Stacked tungsten collimators

5.2. Results – scanning of a geological sample

The device also appears promising in terms of the possibility of analyzing rock samples from diffusion cells, where the activity along the sample axis is determined, to examine the water permeability of the sample with appropriate radioactive salt.

Geological samples are used for the study of intergrains permeability of granite for the purpose of safety of deep deposition of radioactive waste into geological formations, enabling the description of migration processes taking place in the rock environment

Samples with the size of ø50x10 mm are obtained from deep well drilling wells in the monitored area.

On a 3D scanner, geological samples were evaluated after a diffusion experiment where the sample is placed between two reservoirs with a suitable solution. The Intake Reservoir contains radioactive tracer (^{134}Cs), the Outlet Reservoir is inactive. The diffusion is then determined based on the increase in the activity of the outlet reservoir.

The 3D analysis of the spatial distribution of the activity of the tracer in a geological sample after the realization of the diffusion experiment is shown in Figure 7. The analysis allows the tracer to be propagated around the disturbance in the granite or the intergrains permeability of the intact granite.

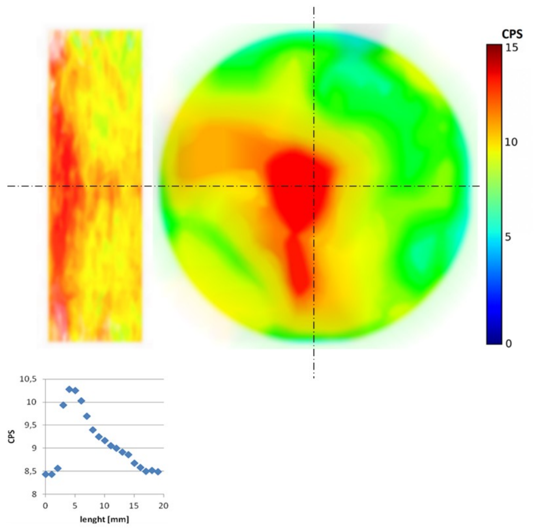

Figure 7. A side profile (left) and floor plan (right) of 3D scan of a granite sample, with a deposited activity of 160 kBq ^{134}CsCl diffusing through the sample from left to right, is shown in the upper part of this figure. Resolution: 8 mm^3 per voxel, scanning time: 36 hours. The plot of activity distribution along the sample axis is shown in the bottom part of this figure.

6. Conclusion

The scanner was primarily designed for the 3D imaging of samples activated at nuclear reactor to the activity levels from 1 MBq to 1 TBq and will be in operation within the hot cells at Research Centre Rez.

It has been optimized by several 3D scans of the radionuclide source ^{137}Cs of 3 mm in diameter and of 10 MBq activity eccentrically stored within a homogenous 10 mm thick steel capsule. That has been successfully scanned and the 3D distribution of activity was computed.

To detect a fine crack (about 0.5 mm) artificially formed inside a small prism (10 x 10 x 20 mm) of activity 1 MBq of ^{60}Co, an ultrafine scan of the sample with a 0.5 mm longitudinal and transverse step and 18° angular step was carried out.

The scanning lasted for 26 hours. The crack has been well visible on a 3D scan as a dark blue curve roughly in the middle of the image.

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