THE DEVELOPMENT OF 3-D TOMOGRAPHY METHOD BASED ON GAMMA-SCANNING OF IRRADIATED FUEL RODS

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Abstract

The tomographic method, consisting in the reconstruction of the images from their projections, is a relatively new nondestructive method, used in the post-irradiation examination of the nuclear fuel. The purpose of the method is to determine the distribution of gamma radioactive fission products in a cross-section of an irradiated nuclear fuel rods. More than 40 fuel rods were investigated at the INR hot cell facility, using this nondestructive technique. The method is used in conjunction with the gamma scanning method and the equipment used for tomographic investigation of the irradiated nuclear fuel is the same to that usually used for gamma scanning investigation.

The paper presents the principles of the Gamma Emission Computed Tomography (GECT), as well as the results and performance of this method, when applied to the investigation of some types of fuel rods, irradiated in the TRIGA 14 MW_{th} materials testing reactor.

1. Introduction

Gamma Emission Computed Tomography (GECT) was used in the last years to evaluate, in a nondestructive manner, the distribution of the gamma radioactive fission products in the cross section of irradiated nuclear fuel rods. The shape of this distribution depends on the neutron flux but also on the behavior of the nuclear fuel during irradiation, especially on the migration of some fission products. Consequently it can be used in diffusion kinetics studies [1], in the determination of the release rate of fission products leaving overheated fuel in case of a severe accident [2] or can offer information about the chemical speciation of the fission products [3].

In the usual post-irradiation examination at the INR Pitesti hot cell facility, the mentioned distribution is used to:

- model the process of the emission and propagation of the gamma photons in the fuel rod, in order to permit a correct estimation of the self-absorbtion coefficient [4];
- highlight the radial migration of some fission products;
- decide on the integrity of the cladding of the fuel rod [5].

2. Method

In GECT, the usual approach is to represent the two-dimensional function f, that describes the distribution of fission products in a cross-section of a fuel rod, on a rectangular grid, composed by square-shaped elements *(i,j)*, called pixels. Experimentally, there are measured projections of the original distribution for more projection angles. A projection p (Fig. 1) is obtained by successive and equidistant displacements of fuel rod in front of a parallel collimator. A projection element p_{km} is a measurement of the gamma emission coming from a narrow strip of the fuel rod, focused by the collimator. The relationship between the two dimensional function f and its projections p is

$$p_{km} = \sum_{i,j} w_{ij,km} f_{ij} \quad (1)$$

where $w_{ij,km}$ is the weighting factor with each pixel *(i,j)* contributes at the projection element p_{km}, which includes also information about attenuation and collimator transmittance.

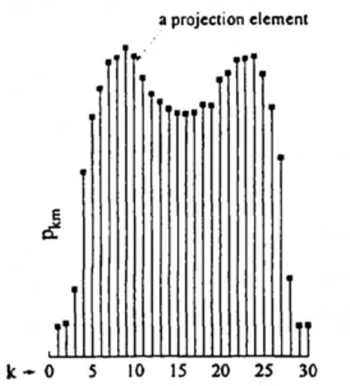

Fig.1 A projection (composed from 30 projection elements * k=1...30) at projection angle "m"

In the particular case of irradiated nuclear fuel rods, the specific problem in the tomographic reconstruction is the small number of projections that can be measured in a reasonable time: the sample is placed in a hot cell and its radioactive content is measured via a long collimator which determines a small detection efficiency, and a long time for the acquisition of the experimental data. In consequence, only a small number of projections can be obtained in a reasonable time. Therefore, Eq.1 provides incomplete data. A supplementary criterion must be introduced to compensate the lack of information. Such a criterion is the maximization of the informational entropy of the system of N x N pixels [6,4]:

$$-\sum_{i,j} f_{ij} \ln(f_{ij}) \quad (2)$$

taking into account the experimental data via Lagrange multipliers (Eq.1). Also, different other methods could be used [7].

3. Experiments and results

The above described method was used in several experiments. We report here the GECT results, obtained in the framework of the non-destructive post-irradiation examination of some types of fuel rods, irradiated in the TRIGA 14 MW_{th} materials testing reactor. Measurements were performed using the system dedicated for usual γ-scanning tests: the image data aquisition device consists of a sample support, which permits the movement of the sample in both vertical and horizontal planes and rotation around its axis, all movements being powered by steping motors, a rotable variable slit collimator and a HPGe detector. In order to minimize the total investigation time, in all experiments we are using five equidistant projection angles. This geometry ensures a reasonable resolution of the reconstructed distributions. Because the isoptope ^{137}Cs is an important fission product for the post-irradiation examination, the results coresponding to this isotope are reported here.

- **An experimental CANDU 6 type fuel rod (containing natural UO_2 pellets), with a burn-up of 153 Mwh/kgU at the end of irradiation**

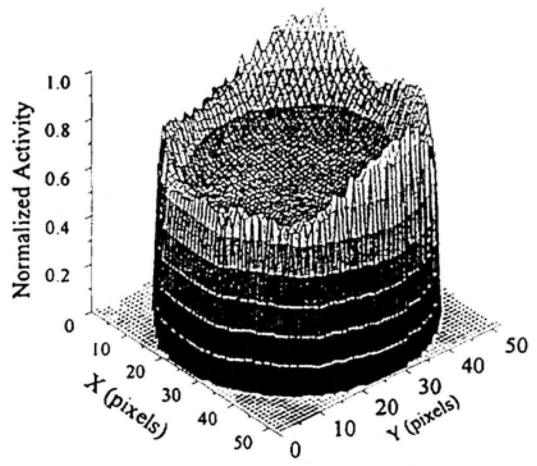

Fig. 2 Reconstruction of the ^{137}Cs distribution in a cross section of an experimental CANDU 6 type fuel rod (containing natural UO_2 pellets)

This fuel rod was irradiated a long period of time (about seven years) in the TRIGA 14 MW_{th} materials testing reactor, but all time at the limit of the active core of the reactor, where the neutron flux is weaker. Its position was often changed during irradiation and, in consequence, the reconstruction of the ^{137}Cs distribution in a cross section of this fuel rod, presented in Fig.2, has a uniform form. The entire diameter of the rod is covered by 50 relative displacements in front of the collimator having a slit of 0.25 mm and, as a consequence, a reconstruction grid of 50 x 50 pixels is obtained.

- **An experimental CANDU 6 type fuel rod (enrichment 5.75% in ^{235}U) with a burn-up of 211 Mwh/kgU, which presents the migration phenomenon of the ^{137}Cs**

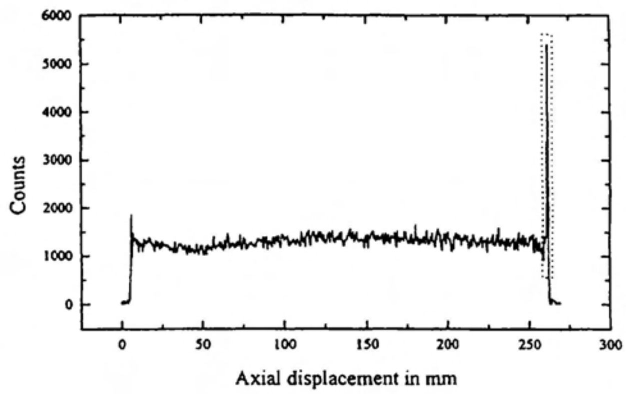

Fig. 3 Axial profile of isotope ^{137}Cs (662 keV) of an experimental CANDU 6 type fuel rod (5.75% ^{235}U)

This experimental fuel rod was irradiated together with other five fuel rods, as an assembly in the TRIGA 14 MWth reactor core, in the 100 kW Pressurized Water Irradiation Loop, in a power ramp test, characterized by the following specific operating parameters:

- fuel rod linear power, before ramping: 43 kW/m;
- fuel rod linear power, after ramping: 64 kW/m.

The total time of irradiation was about 7000 hours.

For this fuel rod are presented both the axial distribution of ^{137}Cs (Fig.3) and the transversal distribution of ^{137}Cs (Fig.4), obtained by GECT reconstruction.

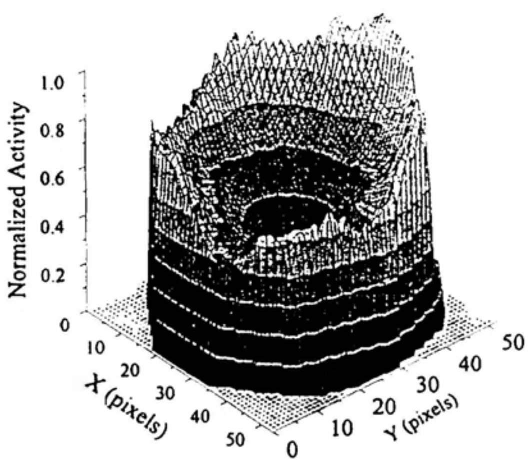

Fig. 4 Reconstruction of the ^{137}Cs distribution in a cross section of an experimental CANDU 6 type fuel rod (5.75% ^{235}U)

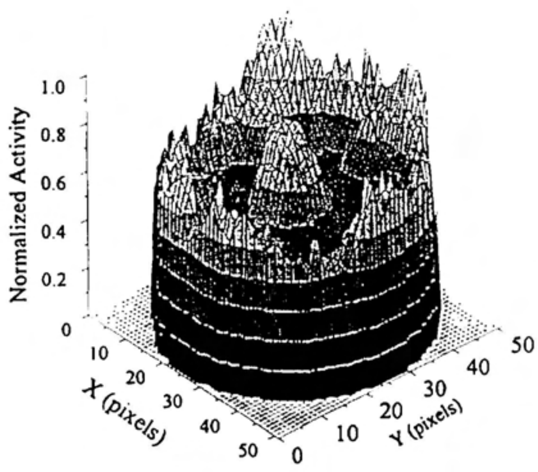

Fig. 5 Reconstruction of the ^{140}La distribution in a cross section of an experimental CANDU 6 type fuel rod (5.75% ^{235}U)

Fig.3 shows an important accumulation of ^{137}Cs on the last millimeters of the fuel rod and the lack of pellets interfaces; these things provide for a axial migration of the isotope did occur. Also, the shape of the transversal distribution of ^{137}Cs, presented in Fig.4, shows a large depression of activity

in the middle of the fuel rod; for this reason, we concluded that ^{137}Cs migrated from the middle region of the fuel rod, with high temperature, to the outer colder regions.
An interesting distribution was obtained for the ^{140}La isotope (1596 keV); its tomographic reconstruction is presented in Fig.5 and it shows an important accumulation of ^{140}La in the middle region of the fuel rod. For the tomographic reconstructions in Fig.4 and Fig.5 it was used a 50x50 pixel plane, using a 0.25 mm width collimator slit; the aquisition of both ^{137}Cs and ^{140}La was recorded in parallel.

- **An experimental CANDU 6 type fuel rod (enrichment 2.53% in ^{235}U) with a burn-up of 193 Mwh/kgU, failed in operation**

If a fuel rod failure do occur, this causes a release of fission products into the primary coolant system. Fission gases accumulated in the free volume of a fuel rod escape through the clad defect. Water entering the fuel rod reacts with fission products, forming volatile chemical compounds. These volatile compounds may escape in like manner to the fission gases, other compounds may dissolve and be carried outside the fuel rod as dissolved species. Consequently, the distribution of these fission products, in the cross section of the fuel rod, is modified. GECT is used to obtain such distributions, in the area of the fuel rod suspected to be damaged. These distributions will be compared with the distributions obtained on an intact fuel rod, irradiated in the same conditions and which has the same characteristics. A significant difference between the shapes of these distributions emphasizes that a failure of the cladding material occurred.

Here are reported some results obtained in an experiment consisting in a power ramp test for an assembly of six experimental CANDU 6 type fuel rods, irradiated in the existing 100 kW Pressurized Water Irradiation Loop of the TRIGA 14 MWth reactor. The test was characterized by the following specific operating parameters:

- fuel element linear power, before ramping: 35 kW/m;
- ramp rate: 0.025 kW/ms;
- fuel element linear power, after ramping: 56 kW/m.

In order to obtain a burnup of about 195 MWh/kgU, the total time of irradiation was planned to be about 5500 hours.
At the beginning of the ramp phase, performed at the end of the irradiation, a failure of the fuel cladding of one of the irradiated rods occurred. After a visual inspection four suspicious regions, located on four different rods were identified. However the conclusions of this control are uncertain, due to the fact that the surface of the rods was covered by a relatively thick layer of corrosion products. For this reason, it was decided to perform the gamma-scanning and tomographic analysis, as it was described in the previous sections.

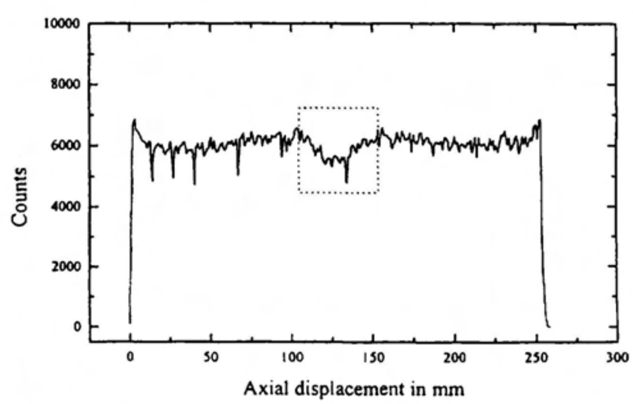

Fig. 6 Axial profile of isotope ^{137}Cs (662 keV) of an experimental CANDU 6 type fuel rod (2.53% ^{235}U) failed

In Fig.6 is presented the axial profile of the distribution of ^{137}Cs for one of the fuel rods suspected for failure; the place where the defect did occur is marked on this profile.
In Fig.7 is presented the reconstruction of the ^{137}Cs distribution in a cross section located in the suspicious region. For the tomographic reconstruction it was used a 25x25 pixel plane, using a 0.50 mm width collimator slit. Also, in Fig.8 is presented the reconstruction of the ^{137}Cs distribution in a cross section of one of the intact fuel rods. The two distributions reveal a significant difference between them, because of one fuel rod is the damaged one. This diagnostic was confirmed later, by

Eddy current control, after removing the layer of corrosion products and by metallographic examination. Similar results were obtained for the other three suspicious regions.

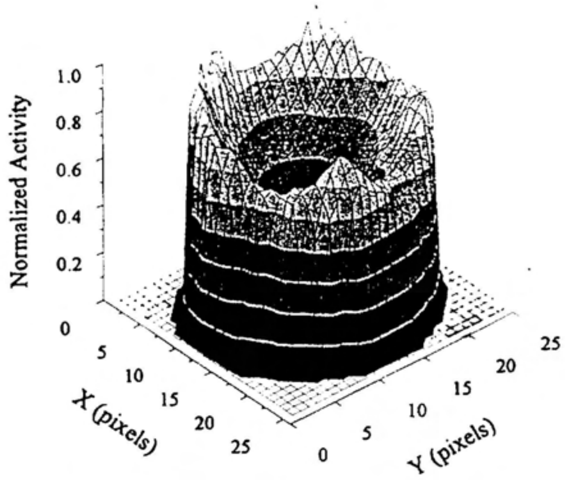

Fig. 7 Reconstruction of the ^{137}Cs distribution in a cross section of an experimental CANDU 6 type fuel rod (2.53% ^{235}U) failed

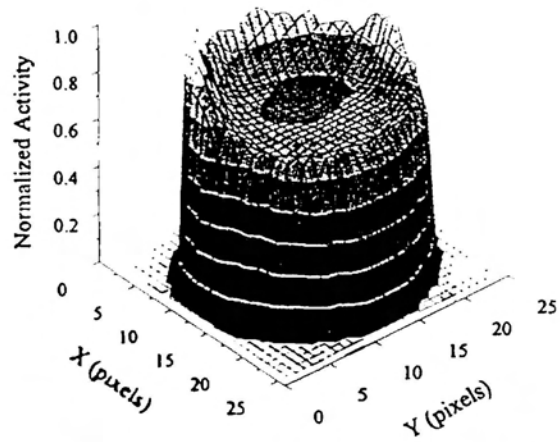

Fig. 8 Reconstruction of the ^{137}Cs distribution in a cross section of an integer experimental CANDU 6 type fuel rod (2.53% ^{235}U)

In conclusion, we appreciate that the tomographic method is a powerfull tool for the non-destructive investigation of irradiated nuclear fuel. Good reconstruction of the distributions of radioactive fission products could be obtained for a very small number of projection angles, in a short time.

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