

Idea of an experimental technique for quantitative passive gamma emission tomography on irradiated nuclear fuel assemblies

Peter Jansson [‡]

[‡] Uppsala University, Uppsala, Sweden

Corresponding author: Peter Jansson (peter@jansson.net)

Abstract

An idea is presented in which passive gamma emission tomography of irradiated nuclear fuel is developed to enable quantitative information of the spatial activity distribution of selected isotopes within the fuel rods of the assembly. The idea is based on using well-known calibration sources mounted in the measurement device during measurement. The image reconstruction would include the sources, thereby enable quantification of the activity distribution. Should the idea be proven viable, the outcome would be valuable to the global community dealing with characterisation of nuclear fuel in terms of safety, security, safeguards and fuel development.

Keywords

tomography, nuclear fuel, passive gamma emission tomography, reconstruction, calibration, GET, PGET, QuantGET, QGET

Overview and background

The tomographic reconstruction measurement techniques used widely in medicine have in the recent decades also found its way into the field of characterisation of irradiated nuclear fuel assemblies, see e.g. Smith et al. (2016). One reason why passive gamma emission tomography is useful for nuclear fuel characterisation is that the measurements can be performed non-destructively without touching or dismantling the fuel assembly. The non-destructive property of the measurement is important for safety and security of handling highly radioactive materials that also contain fissionable materials, such as nuclear fuel assemblies that have been irradiated in a reactor. Two examples: a) in post-irradiation examination experiments for e.g. development of new nuclear fuel types, the measurements can be performed on an intact fuel rod which later can be re-inserted into a reactor for further irradiation, see e.g. Jacobsson (2004), Holcombe (2014). b) In

safeguards for non-proliferation of special nuclear materials, the measurements can be performed to identify missing or manipulated fuel rods without the need to dismantle the assembly, see e.g. Jacobsson et al. (1997).

For passive gamma emission tomography applied to nuclear fuel, the images produced in the mathematical reconstruction of the measurement data are usually of a qualitative or relative nature. I.e., images are produced where an image pixel intensity is proportional to the emission rate of a particular gamma energy, or for a range of gamma energies, from the location/area in the fuel assembly corresponding to that pixel.

Recently, it has been identified that quantitative evaluation of the spatial activity distribution of a measured isotope is of interest, so that the image pixel intensity can be used as a direct measure to quantify the activity in the pixel area, e.g. in the unit of Bq/mm^3 , see Fang et al. (2021). Currently existing tomographic measurement devices developed for nuclear fuel studies contain one or a set of detectors that measure the radiation intensity from the measured fuel assembly in many specific directions or measurement locations, see e.g. Jansson et al. (2006), Holcombe (2014), Honkamaa et al. (2014), Smith et al. (2016), Miller et al. (2017). A quantitative evaluation of the activity distribution using these devices would require detailed, and sometimes difficult-to-assess, knowledge of the spatial attenuation distribution of the full measurement geometry as well as a characterised detector system where intrinsic detection efficiencies need to be well understood. Backholm et al. (2020) have tested simultaneous reconstruction of the spatial distributions of both attenuation and activity, however still producing images with relative data used for classification of the presence or absence of a nuclear fuel rod.

Objectives

The idea presented here has the potential to enable quantitative tomographic evaluation without the need to know the intrinsic detection efficiencies of the detectors in the tomographic device.

Impact

Should the idea be validated and proved to be useful, quantitative evaluation of passive gamma emission tomography would be enabled. Detectors in the device could be replaced, e.g. for maintenance purposes, while still allowing the quantitative evaluation of the spatial activity distribution.

Implementation

It is here suggested to mount one or more well-known calibration source(s) that emits gamma radiation with an energy distribution that resembles that what is of interest in the tomographic measurement device, either in one or more points somewhere outside, but not too far away from, the fuel assembly or in an extended shape (e.g. cylindrical, square,

or hexagonal shape) around the fuel assembly. In some cases it might also be possible to mount calibration sources inside the fuel assembly, i.e. in the tubes for instrumentation and/or reactivity control rods. For example, when the spatial activity distribution of ^{137}Cs is of interest, it is suggested to mount calibration source(s) also based on ^{137}Cs to benefit from similar interaction cross sections and gamma radiation transport properties of the emitted energy.

This idea was inspired by Bengtsson et al. (2021), where the total activity of ^{137}Cs inside a nuclear fuel assembly is estimated using a well-known and point-like ^{137}Cs calibration source mounted in the measurement system.

Using the fact that the known calibration sources can be included in the tomographic image reconstruction, the reconstructed image pixels covering them have intensities that can be one-to-one mapped to the well known activities in the sources. Correspondingly, the intensities in all the other image pixels can be calibrated to quantitative, i.e. absolute, numbers on the activity contents in those pixels.

There are some identified important challenges with the presented idea; The activity of the calibration source(s) to be mounted might need to be so large that special safety challenges must be solved before they can be used. The mathematical procedures used for tomographic reconstruction might need to be adapted to utilize of the knowledge of the activity of the references source(s) in the algorithm. The needed uncertainty of the activity of the calibration source(s) might be prohibitively too small to be cost effective.

The feasibility of the idea presented here, including a study of the limitations posed by the challenges identified above, can be assessed using computer simulation programs developed in, e.g., Smith et al. 2016. Experimental tests of the idea could potentially be performed using e.g. the tomographic device presented in Honkamäa et al. 2014 or the laboratory device available at Uppsala University, described in Jansson et al. 2013.

Conflicts of interest

References

- Backholm R, A. Bubba T, Bélanger-Champagne C, Helin T, Dendooven P, Siltanen S (2020) Simultaneous reconstruction of emission and attenuation in passive gamma emission tomography of spent nuclear fuel. *Inverse Problems & Imaging* 14 (2): 317-337. <https://doi.org/10.3934/ipi.2020014>
- Bengtsson M, Jansson P, Bäckström U, Johansson F, Sjöland A (2021) Experimental Method for Verification of Calculated ^{137}Cs Content in Nuclear Fuel Assemblies. *Nuclear Technology* 1-8. <https://doi.org/10.1080/00295450.2021.1880851>
- Fang M, Altmann Y, Della Latta D, Salvatori M, Di Fulvio A (2021) Quantitative imaging and automated fuel pin identification for passive gamma emission tomography. *Scientific Reports* 11 (1). <https://doi.org/10.1038/s41598-021-82031-8>

- Holcombe S (2014) Gamma Spectroscopy and Gamma Emission Tomography for Fuel Performance Characterization of Irradiated Nuclear Fuel Assemblies. Uppsala University URL: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-235124>
- Honkamaa T, Levai F, Turunen A, Berndt R, Vaccaro S, Schwalbach P (2014) A prototype for passive gamma emission tomography. In: International Atomic Energy Agency (IAEA) (Ed.) Symposium on International Safeguards: Linking Strategy, Implementation and People. IAEA Safeguards Symposium - IAEA CN-220. URL: <https://inis.iaea.org/collection/NCLCollectionStore/External/safeguards/symposium/2014/home/eproceedings/sg2014-papers/000189.pdf>
- Jacobsson S, Bäcklin A, Håkansson A, Jansson P (1997) A tomographic method for experimental verification of the integrity of a spent nuclear fuel assembly. In: European Safeguards Research and Development Association (ESARDA) (Ed.) Proceedings from the 19th ESARDA Annual Symposium.
- Jacobsson S (2004) A Tomographic Measurement Technique for Irradiated Nuclear Fuel Assemblies. Uppsala University URL: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-4227>
- Jansson P, Jacobsson Svård S, Håkansson A, Bäcklin A (2006) A Device for Nondestructive Experimental Determination of the Power Distribution in a Nuclear Fuel Assembly. Nuclear Science and Engineering 152 (1): 76-86. <https://doi.org/10.13182/nse06-a2565>
- Jansson P, Grape S, Jacobsson Svård S, Håkansson A (2013) A laboratory device for developing analysis tools and methods for gamma emission tomography of nuclear fuel. In: The European Safeguards Research & Development Association (ESARDA) (Ed.) The 35th ESARDA Annual Meeting. URL: <http://publications.jrc.ec.europa.eu/repository/bitstream/JRC83924/lcna26127enn.pdf>
- Miller E, Smith L, Wittman R, Campbell L, Deshmukh N, Zalavadia M, Batie M, Mozin V (2017) Hybrid Gama Emission Tomography (HGET): FY16 Annual Report. PNNL Technical Report <https://doi.org/10.2172/1390447>
- Smith E, Svård SJ, Mozin V, Jansson P, Miller E, Honkamaa T, Deshmukh N, White T, Wittman R, Trellue H, Grape S, Davour A, Vaccaro S, Andersson P, Holcombe S (2016) A Viability Study of Gamma Emission Tomography for Spent Fuel Verification: JNT 1955 Phase I Technical Report. Pacific Northwest National Laboratory. PNNL Technical Report PNNL-25995. URL: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-306584>