ARTICLE IN PRESS

Annals of Nuclear Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Applying image analysis techniques to tomographic images of irradiated nuclear fuel assemblies

Anna Davour [a], Staffan Jacobsson Svärd [a,*], Peter Andersson [a,b], Sophie Grape [a], Scott Holcombe [b], Peter Jansson [a], Mats Troeng [c]

[a] Dept. of Physics and Astronomy, Uppsala University, Sweden
[b] OECD Halden Reactor Project, Halden, Norway
[c] Muning. 6, Uppsala, Sweden

ARTICLE INFO

Article history:
Received 14 March 2016
Received in revised form 23 May 2016
Accepted 24 May 2016
Available online xxxx

Keywords:
Nuclear fuel
Image analysis
Gamma emission tomography
Nuclear safeguards

ABSTRACT

In this paper we present a set of image analysis techniques used for extraction of information from cross-sectional images of nuclear fuel assemblies, achieved from gamma emission tomography measurements. These techniques are based on template matching, an established method for identifying objects with known properties in images.

We demonstrate a rod template matching algorithm for identification and counting of the fuel rods present in the image. This technique may be applicable in nuclear safeguards inspections, because of the potential of verifying the presence of all fuel rods, or potentially discovering any that are missing.

We also demonstrate the accurate determination of the position of a fuel assembly, or parts of the assembly, within the imaged area. Accurate knowledge of the assembly position enables detailed modelling of the gamma transport through the fuel, which in turn is needed to make tomographic reconstructions quantifying the activity in each fuel rod with high precision.

Using the full gamma energy spectrum, details about the location of different gamma-emitting isotopes within the fuel assembly can be extracted. We also demonstrate the capability to determine the position of supporting parts of the nuclear fuel assembly through their attenuating effect on the gamma rays emitted from the fuel. Altogether this enhances the capabilities of non-destructive nuclear fuel characterization.

1. Introduction

1.1. Gamma emission tomography of nuclear fuel

Nuclear fuel consists of rods made of uranium dioxide pellets stacked in tubes of a corrosion-resistant material. The rods are mounted in assemblies which can be moved into a nuclear reactor where the uranium undergoes fission. Typically, a fraction of the fuel inside a reactor core is replaced every 12–18 months.

The fuel is heavily irradiated by neutrons and other particles during its time inside a reactor core. Fission products build up within the fuel rods, and this changes the chemical and mechanical properties of a fuel rod. The supporting materials may also be affected through neutron activation. Thus, irradiated nuclear fuel contains many different radioactive isotopes with varying half-lives.

The gamma radiation field around a used nuclear fuel assembly contains information about the distribution of the various radioactive isotopes decaying within the assembly. The internal structure of the assembly can be tomographically reconstructed from measurements of the gamma emission from the decaying isotopes within the fuel. The reconstruction results can be used for applications in nuclear safeguards (Sokolov et al., 2008; White et al., 2015) as well as for fuel performance characterization (Holcombe, 2014).

This article serves to give an overview of some image analysis techniques used on experimental gamma emission tomography images of irradiated nuclear fuel assemblies, to present the basic principles of their functionality and to demonstrate their performance. We discuss image analysis as a supporting technique to extract information from the cross sectional images reconstructed from gamma emission measurements.

Images are created from the measured gamma flux distribution using two main types of reconstructions (Jacobsson Svärd et al.,

* Corresponding author.
E-mail address: staffan.jacobsson_svard@physics.uu.se (S. Jacobsson Svärd).

http://dx.doi.org/10.1016/j.anucene.2016.05.024
0306-4549/© 2016 Elsevier Ltd. All rights reserved.

2015b). One kind is based on analytic algorithms, known as filtered back-projection (FBP), and results in images such as the ones analysed in this work. Algebraic algorithms, on the other hand, can be used to create images or to return more accurate quantitative information about the gamma emission from each fuel rod. Extracting such conclusive rod-wise data requires detailed modeling of the attenuation of the gamma radiation within the measured fuel assembly, and to do this it is crucial to have accurate knowledge of the location of each fuel rod within the measured area (Jacobsson Svärd et al., 2015b). As we shall see, image analysis can be a helpful tool to provide this input to an algebraic reconstruction of rod activities.

1.2. Applications for fuel performance characterization

If the measurement allows for separation of the gamma emission lines in the energy spectrum, the distribution of fission products within the fuel rods as well as activation products in the supporting materials can be imaged. This as has been shown in tomographic measurements of fuel assemblies at the Halden Reactor Project (HRP) (Holcombe et al., 2015). In similar ways, other research groups have studied the distributions of different isotopes by analysing the gamma emission field of single fuel rods (Caruso and Jatuff, 2014; Caruso et al., 2009; Craciunescu et al., 1995; Sawicka and Palmer, 1988).

With spectroscopic information, it may also be possible to reconstruct information such as burnup for each fuel rod, and even to determine the cooling time, i.e. the time after removal from the reactor (Jansson, 2002; Jacobsson Svärd et al., 2015a). Again, the capability to use image analysis methods to determine the exact position of the measured objects within the measurement apparatus is necessary to extract this type of high-precision rod-wise data.

1.3. Applications for nuclear safeguards

Nuclear safeguards are the measures implemented to ensure the peaceful use of nuclear materials and technologies. The inspection of fuel being moved into deep underground storage, where it will be difficult to access, is an important safeguards application for gamma emission tomography and imaging (Lundqvist et al., 2007). Before being moved to this kind of storage, the IAEA (the International Atomic Energy Agency) requires that any nuclear fuel that is designed in such a way that it can be disassembled is verified with a method that allows for discovery of partial defects, i.e. missing or substituted parts of the fuel. Alternatively, if no such method is at hand, the fuel integrity should be verified using the best available method (IAEA, 2010). Development of new inspection tools for partial defect tests before transfer to difficult to access storage is a high priority task in the IAEA R&D plan (IAEA, 2013), and gamma tomography shows great promise for providing such a tool.

Image analysis is already used in other nuclear safeguards applications, although mostly in ways that differ considerably from our work. For example, image change detection techniques may be used to monitor compliance with international treaties. This has been applied in camera surveillance (Howell et al., 1995) at nuclear facilities. At a larger scale, change detection techniques are used in the analysis of satellite images (Jasani et al., 2009) to monitor activity at facilities and verify that there are no undeclared nuclear activities.

An example of another imaging application with partial defect detection capability is the Digital Cherenkov Viewing Device (DCVD), imaging the Cherenkov radiation of fuel in wet storage pools. It has been shown that image analysis techniques can be used to improve the quantitative information that can be extracted from DCVD images (Branger et al., 2014).

2. Gamma emission tomography experiments

Nuclear fuel assays using gamma emission or gamma transmission tomography have been performed in different experiments and contexts. The methods described in this paper are developed for analysis of tomographic images of entire fuel assemblies rather than individual fuel rods. Here we focus on three instruments which have been built and tested specifically for measurements on entire assemblies, illustrated in Figs. 1 and 2.

The tomographic test platform PLUTO (Jansson et al., 2006) was designed at Uppsala University and used in measurements at the Forsmark nuclear power plant in 2002. Four scintillator (BGO) detectors were mounted in a tungsten collimator block, which could be moved around the assembly and also shifted laterally in the direction perpendicular to the collimator slits, as shown in Fig. 1 (left). The position of the assessed fuel within the PLUTO apparatus was determined with independent mechanical measurements.

The second instrument is called PGET (Passive Gamma Emission Tomograph), developed within the IAEA support program task JNT 1510 (Sokolov et al., 2008). This device has been employed in three imaging experimental campaigns 2012–2014 (Honkamaa et al., 2014). Here, 208 CdTe detectors are mounted behind tungsten collimators, in two detector heads that are placed on opposite sides of the fuel assembly, as shown schematically in Fig. 1 (right). These heads are simultaneously turned around their common centre to measure from different angles, and rely on use of the many detectors instead of lateral translations in order to cover the full width of the fuel.

Other experiments use one single HPGe detector to do detailed investigations of the distribution of different isotopes within fuel assemblies or single fuel rods. This type of detector gives excellent spectroscopic resolution, but the measurements are more time consuming than for setups with several smaller detectors measuring in parallel as in the PLUTO and PGET devices. The tomography device at the Halden research reactor (Holcombe et al., 2015), shown in Fig. 2, is of this type.

The basic technique is the same for all of the described experiments: the gamma radiation is measured at a number of positions, in the same axial plane, around the fuel. Collimators ensure that one detector is viewing photons emitted at a certain angle, from a narrow region of the fuel. A large number of data points (typically $10^3 - 2 \cdot 10^4$) make up the input to a tomographic reconstruction algorithm, and the result can be presented as a two dimensional picture of the cross section of the fuel assembly.

3. Image analysis techniques applied on tomographic images of nuclear fuel assemblies

3.1. Basic considerations

Digital images are composed of discrete picture elements, pixels, which are assigned values that can be graphically represented as colour or light intensity. Digital image processing is widely used to extract information from images. One everyday example is the commonly used barcode reader. Image analysis is an active research field, covering all kinds of problems where computers are used to create, interpret or modify images. Many examples can be found in medical imaging. The techniques used to extract information from digital images vary depending on application.

In the tomographic images analysed in our work, we want to locate fuel rods. These are identified as specific features of a well-known geometry (circular objects in a distinct pattern) in the collected 2D images. For this purpose, we focus on a pattern recognition technique using template matching.